

FINAL REPORT

ON

INVESTIGATION OF STORAGE SYSTEM DESIGNS AND TECHNIQUES FOR OPTIMIZING ENERGY CONSERVATION IN INTEGRATED UTILITY SYSTEMS

VOLUME III

(ASSESSMENT OF TECHNICAL AND COST CHARACTERISTICS
OF CANDIDATE IUS ENERGY STORAGE DEVICES)

MARCH 10, 1976



BATTELLE
COLUMBUS LABORATORIES
505 KING AVENUE
COLUMBUS, OHIO 43201

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PREFACE

There are three volumes in a set comprising the final report on "Investigation of Storage System Designs and Techniques for Optimizing Energy Conservation in Integrated Utility Systems", prepared by Battelle's Columbus Laboratories for the Urban Systems Projects Office at NASA, Johnson Space Center, under Contract No. NAS 9-14628. The volumes are entitled:

- Volume I - Executive Summary
- Volume II - Application of Energy Storage to IUS
- Volume III - Assessment of Technical and Cost Characteristics for Candidate IUS Energy Storage Devices.

Volume III is a collection of monographs which discuss each of the energy storage categories assessed in the study. It is thought that this volume will not only serve as a backup reference for Volumes I and II, but also serve as an introductory work for readers who have an interest in energy storage technology, but have not been exposed to much of the literature in this area. Volume III, therefore, briefly covers the basic theory of operation of each of the energy storage categories and contains extensive reference lists which serve as a guide to the information available.

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1. INTRODUCTION

The central issue of this study was identified and discussed in detail in the preceding Volumes I and II. It is briefly restated below to indicate the primary focus for this volume of supporting technical material.

"As part of the continuing quest for methods of conserving energy and minimizing costs, this study has been directed at examining the potential role of energy storage in the conceptual setting of the Integrated Utility System (IUS)."

Battelle's recent participation in a previous program on energy storage for electric utility application^{(1)*} served as a useful point of departure for the subject study despite some obvious differences in the scale of application (i.e., the gross difference in the power/energy levels involved). The six energy storage technologies (inertial, superconducting magnetic, electrochemical, chemical, compressed air, and thermal) covered herein were all previously assessed by the Battelle teams and were reevaluated for specific applicability to the IUS. A seventh technology reported in Reference 1, viz, underground pumped hydro, was excluded from this study, because it was anticipated that restrictive siting requirements would be a severely limiting factor.

To provide a perspective for the individual storage technologies, a brief outline of the general nature of energy storage and its significance to the user is presented in the following section.

* Superscript numbers refer to references listed at the end of each major Section of this Volume.

Reference for Section 1

- (1) Schneider, T. R., "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities", Public Service Electric and Gas Company, Final Report on ERDA Contract Number E(11-1)-2501 and EPRI Research Project 225 (December, 1975), Three Volumes.

2. GENERAL BACKGROUND ON ENERGY STORAGE

The general notion of storing energy for release (i.e., power generation) at a desired time is certainly not new in view of the fact that any form of fuel is an energy store. Perhaps the most general observation that can be made about energy storage is that it affords the means for smoothing out duty cycles that exhibit large excursions from the ideal match between power supply and demand. That is, under those circumstances when power is (inherently and/or desirably) being generated continuously, it may be cost-effective to store excess energy during "off-peak" demand time intervals and to recover it for peak demand utilization. The fundamental trade-off involved is the acceptance of inefficiencies and cost associated with energy storage to gain whatever technical and economic advantages occur from more flexible allocation and control of resources for power generation.

Although the preceding generalizations are valid for practical scenarios involving useful energy/power transformations (e.g., for transportation vehicle propulsion), the implications for electric power generation are among the most compelling in applied technology today. A variety of reasons have accumulated to focus intense interest on this technological area.

- An electric power generating system must have sufficient capacity to meet peak demand plus reserve capacity to assure reliability of power delivery. However,
 - Duty cycle characteristics are such that a significant amount of capital intensive generating equipment is idle over sizeable portions of the cycle,
 - Capital costs for generating equipment are increasing rapidly and equipment delivery lead times are lengthening,

- o Operational and maintenance costs, especially for fuel, are escalating rapidly to the point of challenging the cost-effectiveness of equipment that use premium fossil fuels (oil and natural gas).
- Concerns over global control of fuel production and over dwindling reserves of premium fossil fuels have become dominant driving forces for fuel conservation.
- Concern over environmental quality is a staunchly supported driving force for air and water quality control and for stricter land use policy, in relation to power plant siting.
- Assumption of increased nuclear power availability and resurgence of (as yet) relatively plentiful and low-priced coal may make the charging energy storage devices during off-peak demand periods a much more attractive/necessary proposition.

These reasons, then, are forcing planners to reexamine existing mixes of power generation equipment and future acquisition to meet an ever increasing load.

Energy storage appears to have a potentially important role in this situation. The technical details and strategies involved are complex, as evidenced in the literature⁽¹⁻¹²⁾. Most of the attention thus far has been devoted to either rather small scale applications (transportation) or to very large scale systems (electric utilities), and little to the intermediate power/energy regime exemplified by the IUS. Thus, it is in this context that energy storage technologies are reassessed in the following sections. Details of the selected IUS application scenarios are described in Volume II of this final report.

References for Section 2

- (1) Kline, L. V., Marco, S. M., and Starkey, W. L., "Work Capacities of Energy Storage Systems on Basis of Unit Weight and Unit Volume", Transactions of the ASME, 80 (1958) p 909.
- (2) Daniels, F., "Energy Storage Problems", Proceedings of the Conference on New Sources of Energy, Volume 11, General Sessions, United Nations (1963) p 156.
- (3) Bruckner, A., Fabrycky, W. J., and Shamblin, J. E., "Economic Optimization of Energy Conversion with Storage", IEEE Spectrum, 5 (4) (April, 1968) p 101.
- (4) Cutter, W. H., "Gas Generators--A Perspective", AIAA Paper 73-1168 (November, 1973).
- (5) Fernandes, R. A., Gildersleeve, O. D., and Schneider, T. R., "Assessment of Advanced Concepts in Energy Storage and Their Application on Electric Utility Systems", IXth World Energy Conference (1974) Session 6.1 Paper 17.
- (6) Vanderryn, J., "Energy Storage Technology", Converting Existing Hydro-Electric Dams and Reservoirs into Pump Storage Facilities, Engineering Foundation Conference (August, 1974).
- (7) Kalhammer, F. R., "Energy Storage: Incentives and Prospects for Its Development", American Chemical Society Annual Meeting, Atlantic City, New Jersey (September, 1974).
- (8) Kalhammer, F. R., and Zygielbaum, P. S., "Potential for Large-Scale Energy Storage in Electric Utility Systems", ASME Paper 74-WA/Ener-9 (November, 1974).
- (9) Ricci, L. J., "Utilities Eye Large-Scale Energy Storage", Chemical Engineering, 82 (3) (3 February, 1975) p 24.
- (10) Kalhammer, F. R., "Energy Storage: Applications, Benefits, and Candidate Technologies", Electrochemical Society Annual Meeting, Dallas, Texas (October, 1975).
- (11) Braun, C., Cherniavsky, E. A., and Salzano, F. J., "The Economic Incentive for Introducing Electric Storage Devices into the National Energy System", Record of the Tenth Intersociety Energy Conversion Engineering Conference, IEEE (August, 1975) p 82.
- (12) Rumbaugh, J. H., "Factors to be Considered in the Implementation of a Central Storage Facility", Compressed Air Energy Storage Workshop, ERDA and EPRI, Warrenton, Virginia (December, 1975).

3. INERTIAL ENERGY STORAGE

Basic Aspects of Inertial Energy Storage

The practical basis for inertial energy storage is the kinetic energy associated with a rotating mass that is radially and circumferentially symmetric about the axis of rotation. Elementary rigid body mechanics yield the following useful relationship for specific energy "stored" in a rotating mass, viz.,

$$(\text{Kinetic energy per unit mass}) \propto \left(\frac{\text{Allowable stress}}{\text{Density}} \right)$$

In equation form, this relationship becomes

$$E = K_s \frac{\sigma}{\rho} \quad (1)$$

where the constant of proportionality, K_s , characterizes the mass distribution and has been appropriately termed the "shape factor". K_s can be defined by choice of units to range from 0 to 1.

It can also be found from similar arguments that the corresponding specific angular momentum has the form

$$H = r_o \left(2K'_s \frac{\sigma}{\rho} \right)^{1/2} \quad (2)$$

where the modified shape factor, K'_s , is related to K_s in Equation (1) by the radius of gyration, k , and (for practical convenience) the outer radius of the rotating mass, r_o ; that is,

$$K'_s = \left(\frac{k}{r_o} \right)^2 K_s \quad (3)$$

Note, too, that K'_s can range from 0 to 1.

A rather extensive literature (References 1-51)* manifests the exploitation of either Equation (1) or (2). The term "flywheel" has been loosely associated with energy storage applications; whereas, the use of "momentum wheel" is clearly peculiar to momentum storage. This latter application is germane to the present study to the extent of posing technological problems (e.g., materials, system components, etc.) and suggesting solutions in common with energy storage.

Much of the literature indicates a concentration of effort in relatively small-scale energy storage (i.e., at the levels of tens and hundreds of kilowatt-hours) motivated by automotive and rail vehicle propulsion requirements. It has only been recently that serious attention^(14,51) has been directed toward the multi-megawatt-hour levels in the domain of electric utility peak-shaving. Between these extremes of energy storage lie the needs of the Integrated Utility System (IUS).

Equation (1) is fundamental in configuring the rotating mass to maximize energy storage. However, the feasibility of incorporating an inertial energy storage device into a well constrained system such as the IUS must also include consideration of techniques for (1) transferring energy to and from the rotating mass and (2) minimizing losses during idle time between energy transfers. From these three basic categories of system characteristics, a preliminary schematic concept, such as shown in Figure 3.1, is presented as a means of identifying critical subsystems. Thus: (1) the desire to maximize specific energy storage is associated with the flywheel(s) and shaft; (2) the transfer of energy between the IUS busbar and the flywheels is associated with power conditioning, a motor/generator, and a coupling/gearbox; and (3) loss minimization suggests the criticality of bearings/lubricant, and the desirability of a vacuum enclosure (which, in turn, poses a problem in seals/feedthroughs). Then those considerations, together with the choice of horizontal or vertical shaft orientation and safety considerations, largely determine the support structure.

* This compilation is intended to provide convenient access to documentation.

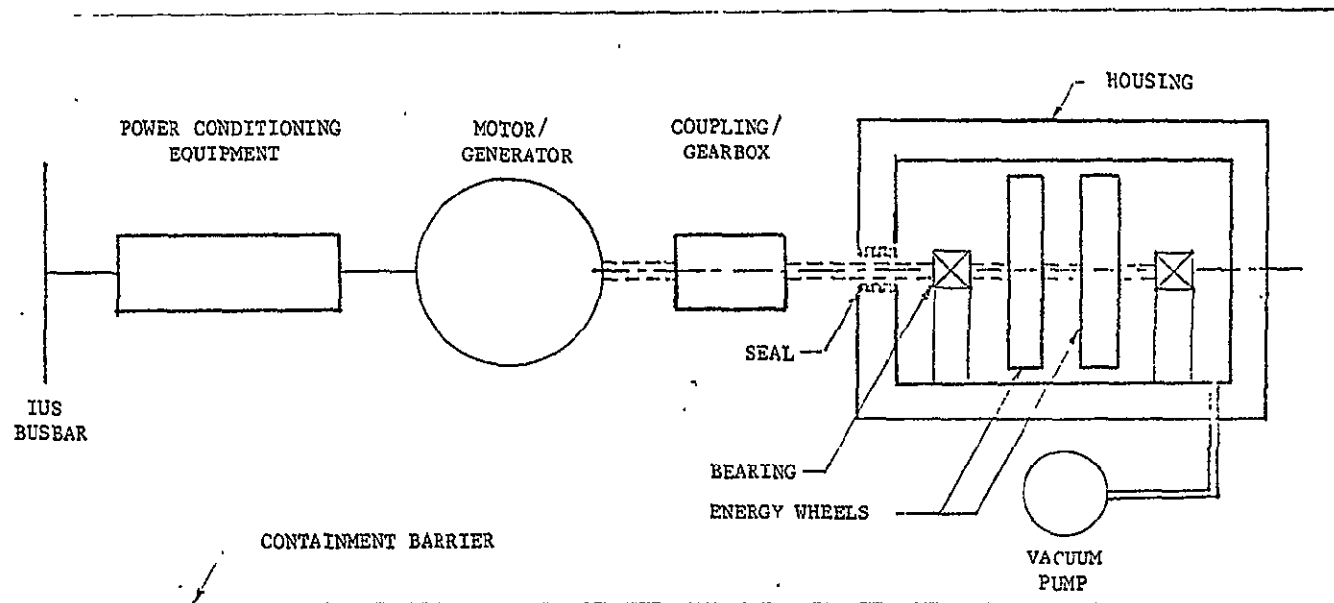


FIGURE 3.1. SCHEMATIC OF AN INERTIAL ENERGY STORAGE CONCEPT APPLIED TO THE IUS

Alternative Approaches for Implementation

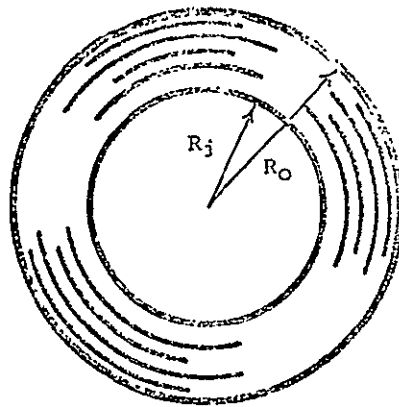
Rotating Mass Configuration. Using Equation (1) as a guideline, an array of shape-material combinations could be constructed. However, such a systematic examination is not necessary, because it can be demonstrated from the literature that some geometries lend themselves better to certain material/fabrication techniques than to others. Four rotating mass configurations have been selected from the References as alternative candidates with a reasonable expectation for successful application to the IUS. They are

- Laminated wheel
- Multirim wheel
- Brush wheel
- Constant-stress wheel.

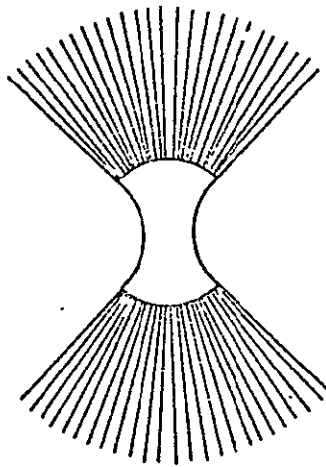
Sketches of several of these configurations are shown in Figure 3.2. Suitable types of materials and fabrication techniques are presented in Table 3.1, which also provides a qualitative summary of several aspects of feasibility.

One of the technological developments that definitely paces the implementation of inertial energy storage devices is that of composite materials (i.e., fibers embedded in a matrix material) which offer attractive σ/ρ values for Equation (1). Four kinds of fiber materials have received the most attention: graphite, fiberglass, aramid, and boron. Various epoxy or polyester resin formulations have served as the most common types of matrix materials.

Unfortunately, some overoptimism about the performance (specific energy, as defined by Equation (1)) of composite material flywheels has resulted from the use of single fiber strand (or tow) strength properties. For example, consider the properties of a commercial graphite fiber listed in Table 3.2. The ultimate tensile strength (UTS) of this fiber is 2.82 GPa (410 Ksi) minimum. However, after accounting for fiber variability, damage in passing winding pulleys and resin volume in the composite material, a minimum UTS in the range of 1.0-1.4 GPa (150-200 ksi) is probably a more realistic value for design. Similarly for a commercial aramid, whose properties are listed in Table 3.3, the minimum tensile strength specified is 3.4 GPa (490 ksi).



(A) Multirim Constant Thickness Wheel



(B) Brush Wheel

FIGURE 3.2. SKETCHES OF CANDIDATE ENERGY
WHEEL CONFIGURATIONS

TABLE 3.1. QUALITATIVE SUMMARY OF CANDIDATE INERTIAL ENERGY STORAGE WHEEL
SHAPE-MATERIAL COMBINATIONS

Concept	Material Type and Availability	Fabricability	Disadvantages	Advantages	Overall Technical Feasibility	As Fabricated Cost
Laminated Isotropic Materials	High-performance steels and titanium. With emergence of this market, specialty steels will be come available in adequate quantities.	Conventional fabrication and joining processes applicable, hence, technology transfer is rapid. Minimal technological development required.	For large flywheels, sheets must be joined. Flywheel size limited due to density of steel.	Simple and fracture tolerant design. High properties of thin materials advantageous. Low cost fabrication and assembly. Can be successively upgraded by substituting higher performance sheet materials.	Highly feasible already in 1976-1980 period. However, there are size limitations due to energy density requirements.	Low
Multirim (Reference 34)	High-strength fibrous composites. Due to emerging commercial markets for advanced composites, e.g., golf clubs and tennis racquets, materials could become available in adequate quantities. However, lead-times and large number of suppliers reducing impact of volume increases, need to be considered.	Due to massive sizes of flywheels foreseen, R&D is required, in particular, to minimize total fabrication cost and to achieve desired quality at acceptable production rates.	A sophisticated design. To optimize configuration, different fibers must be used which increase quality assurance problems. When various fibers are used, considerable test data is required. Quality assurance is complex, resulting in low production rate. Deficiencies in fabrication difficult to rectify.	The concentric ring design allows lower cost, higher performance or heavier materials to be used where optimum. Conventional filament or tape winding fabrication processes are applicable. High volume efficiency. Resilient rings can be incorporated between structural rings. Fracture tolerance can be incorporated in the design concept.	Considerable R&D is necessary. Concept is predicted, however, to be feasible in 1980-1985 period.	Moderate
Brush (References 35, 36, 37, 38, 40, 42)	Unidirectional high-strength filaments in plastic matrices "pultruded" as rods. On fiber availability, see comment above on "Multirim" concept.	Fabrication technology ("pultrusion") currently in advanced stage of development for high-volume commercial applications, e.g., ladders and rails, and also for aerospace hardware.	Rods occupy small portion of swept volume adversely affecting cost and size of system. Rods are stressed unevenly, unless tapered rods are used which pose production problems. Rod anchoring at hub complex, expensive to produce, and causes stress concentration problems. Difficult to maintain balance of flywheel due to shodding or rods.	Fibers are utilized efficiently. Quality assurance (QA) techniques can be automated and incorporated as part of the pultrusion process. Failure of rods is not catastrophic. Assembly on site is simple, as is transportation.	Where the production volume required is cost-effective, the concept is highly feasible in 1976-1980 period.	Low
Constant Stress Configuration (Also producible as laminated concept)	Ideal in metallic materials for small flywheels. For large flywheels in this configuration, hybridized "tailored" laminated concepts of composites and metals (e.g., in foil form) would be attractive.	Fabrication and nondestructive testing expensive and difficult. Excessive machining required when forged metals only are used. Considerable development is necessary to reduce cost.	Large sheet materials in metals and composites required. Difficult to tailor composites at low cost and achieve high fiber loading efficiencies.	Theoretically there is a potential for a "tailored" optimized design with material systems. However, trade-offs with cost are required.	Feasible in the 1980-1985 period. Design for optimization of materials system, cost, and fail-safety will be major factors influencing the acceptability of the concept.	High

TABLE 3.2. PROPERTIES OF CONTINUOUS FILAMENT
GRAPHITE FIBER

Property	Value
Nominal Filament Diameter, μm	7.8-8.1
Average Density, (a) kg/m^3	1780-1830
Weight per Unit - Length of Tow, (a) kg/m	800-900
Ultimate Tensile Strength(a,b) GPa	2.8 minimum
Modulus of Elasticity(a,b) GPa	210-230

Source: Reference 64.

(a) Lot average values.

(b) Lower values are guaranteed minimum
values.

TABLE 3.3. MINIMUM SPECIFICATION REQUIREMENTS FOR A COMMERCIAL ARAMID

	Requirement	
	12-End Roving	4-End Roving
Tensile strength (package average), GPa	3,38 minimum	3,38 minimum
Tensile strength (lot average), GPa	3,45 minimum	3,45 minimum
Tensile modulus, GPa	120 minimum	120 minimum
Weight, kg/m	5×10^{-4}	5×10^{-4}
Density, kg/m ³	1450	1450
End count	12 ± 0	4 ± 0
Fibers/end	267^{+3}_{-0}	768^{+9}_{-0}
Fiber diameter, μm	11.7 nominal	12.0 nominal

However, after accounting for difficulty in winding, sensitivity to matrix resin type, and a fiber volume fraction of 50 percent in the composite, a strength of 1.4 GPa (200 ksi) is probably more realistic for use in Equation (1).

Taking into consideration the above factors, a quantitative supplement to Table 3.1 has been assembled for display in Table 3.4. Note that both optimistic and "realistic" estimates of specific energy (or energy density) are shown.

Of the concepts studied, the multirim configuration executed in metal and composite materials appears to be a promising candidate for IUS application, because of the following features:

- The type, properties, and cost of fibers can be varied radially to optimize the flywheel.
- The fiber volume in the composite can be varied radially.
- The thickness of the rings can be varied radially.
- Because composite structures are built up to size in contrast to machining down to size, materials and energy in fabrication are conserved.
- Interface rings of resilient materials can be incorporated between structural composite rings.
- The composite rings or complete flywheel can be encapsulated with high-performance materials, or high-performance metal strip interleaves can be used for fail-safety or to minimize influence of material and fabrication deficiencies.
- Axially mounted metal discs can be incorporated to compensate for low interlaminar properties of composites.
- Composite winding techniques developed for rocket cases and pressure vessels is largely translatable to the flywheel application, and modifications of equipment developed for military uses and large filament-wound pipes would shorten the lead time.

TABLE 3.4. ENERGY DENSITIES OF CANDIDATE INERTIAL ENERGY STORAGE WHEEL
SHAPE-MATERIAL COMBINATIONS

Material Properties and Energy Characteristics	Flywheel Concept and Material Type	Multi-Rim:			Constant Stress Steel
		Disc Steel	Graphite/Epoxy with Interleaves	Brush Boron Fibers	
Ultimate Tensile Strength, F_{tu} , GPa		1.03	1.38	2.76	1.03
Material Density, kg/m^3		8300	1990	2700	8300
Energy Density, Wh/kg		11-15	88-110	88-110	26-29
Energy/Unit Swept Volume, Wh/ m^3		153-71	106	.02-.035	141-159

Energy Transfer Devices. In References 14 and 51, energy transfer between the electrical power bus and the rotating energy storage device was addressed to the extent of identifying various candidates. Both investigations found favor (from cost and reliability standpoints) with rotating electrical machinery that was essentially a wound rotor induction machine, which featured control of the excitation frequency of the field,* through the use of cycloconverters. A schematic of the system is shown in Figure 3.3. It is believed that this arrangement would also be feasible for the IUS application.

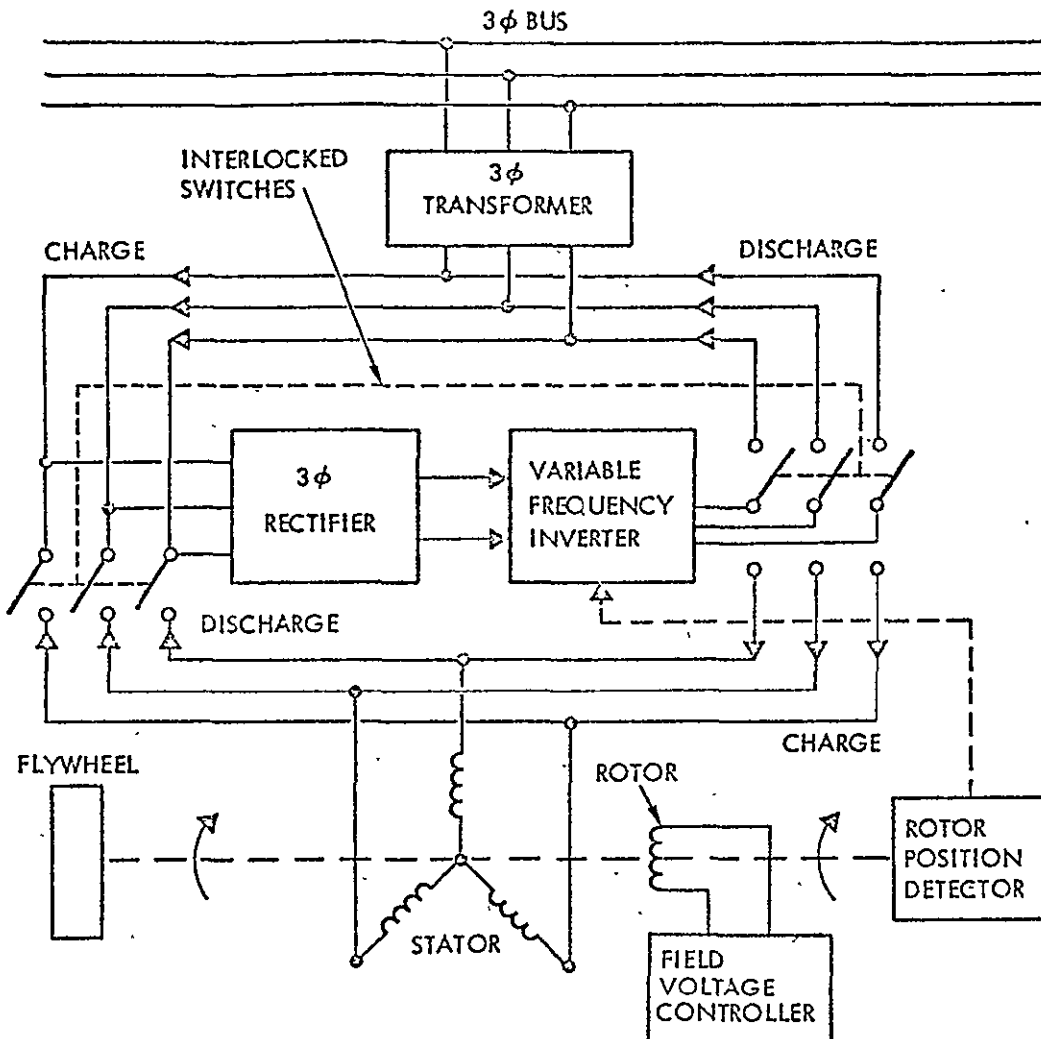
A speed reducer and coupling are required to match the low rotational speed operation of the electrical machinery with the higher speed of the energy storage wheel. Three of these drive train candidates are described in Table 3.5.

Loss Minimization Subsystems. As previously mentioned, loss minimization during idle or "holding" periods points to the criticality of bearing/lubrication subsystem design and to the desirability of a vacuum enclosure.

Over the near term (to 1980) conventional rolling element bearings would probably be the most appropriate for the IUS application. As indicated in Table 3.6, an oil mist lubrication arrangement is suggested as the complement to the bearings. Although magnetic bearings (e.g., see References 52-56) have the appeal of non-contact suspension, the development problems for an IUS application preclude near term consideration.

Next to bearing losses, windage losses of the rotating energy storage mass can also be significant. Thus, vacuum containment with state-of-the-art vacuum pumping equipment is clearly indicated. In Reference 51 a hermetic seal has been recommended via arguments reproduced in Table 3.7. That recommendation has been carried over into this present IUS study. It is recognized that advanced sealing concepts such as the use of ferrofluids are under development (see, for example, References 57-59). However, once again the argument of the development time frame appears to exclude near term use.

* In Reference 14, the scheme is called a "frequency makeup system". In Reference 51, the scheme is called a "variable frequency field machine". The advantages and limitations of such an arrangement are discussed in both documents.



After Reference 14

FIGURE 3.3. ARRANGEMENT FOR ENERGY TRANSFER BETWEEN
ENERGY WHEEL AND IUS BUS

TABLE 3.5. CANDIDATE SPEED REDUCER CONCEPTS FOR INERTIAL STORAGE DRIVE TRAIN

Subsystem	Concept	Advantages	Disadvantages	Conclusions
Speed reducer	Transmission, horizontal shaft, parallel offset	<ul style="list-style-type: none"> • Available off the shelf for near-term applications • 95-98 percent efficient 	<ul style="list-style-type: none"> • Separate lubricant system required • Relatively heavy 	Best for near-term application. Design optimization required for high power applications (>1500 hp)
	Traction drive	<ul style="list-style-type: none"> • Variable ratio (flexibility, optimum generator input speed) 	<ul style="list-style-type: none"> • 90 percent max. efficiency • ~100 hp SOA • Not well suited to high inertial loads and load variations 	May be applied in the future--rotor/generator efficiencies must be traded against cost/complexity of variable speed capability
	Harmonic drive	<ul style="list-style-type: none"> • Relatively simple • Can also serve feed-through function 	<ul style="list-style-type: none"> • Limited to 500 hp • Reduction ratio too high • Life of flex spline at high loads--speeds is uncertain 	Research and development directed at power-speed scale up may make this suitable for second generation high speed (ca 20,000 rpm drives)

TABLE 3.6. CANDIDATE LUBRICATION CONCEPTS FOR INERTIAL ENERGY STORAGE BEARINGS

Subsystem	Concept	Advantages	Disadvantages	Conclusion
Lubricant for rolling element bearings	Grease	<ul style="list-style-type: none"> • Low maintenance • No auxiliary lube system • Good lubrication in low vapor pressure forms 	<ul style="list-style-type: none"> • High viscous drag losses* • Possible thermal problems • No wear debris removal 	Not suitable
	Oil, liquid	<ul style="list-style-type: none"> • May be circulated and filtered, debris removed and bearings cooled • Generally lower drag than grease 	<ul style="list-style-type: none"> • Drag losses can be highly variable • Heat removal not optimum • Auxiliary lube system required 	No optimum with respect to distribution and drag losses
	Oil, mist	<ul style="list-style-type: none"> • Lowest possible drag losses for oil-lubricated bearings • Optimum heat removal and distribution • Good debris removal possibly, not as good as liquid oil flush 	<ul style="list-style-type: none"> • Minimum lubricant quantity, no reserve in event of lube system failure • Debris removal not optimum 	A well designed oil mist system using a low vapor pressure oil appears to be best at this time

TABLE 3.7. CANDIDATE SEAL/FEEDTHROUGH CONCEPTS FOR INERTIAL ENERGY STORAGE

Subassembly	Concept	Advantages	Disadvantages	Conclusion
Seals and feedthroughs	Rubbing seals	<ul style="list-style-type: none"> • Positive • Relatively simple, inexpensive • Allows a one piece shaft, i.e., reduces number of bearings 	<ul style="list-style-type: none"> • High friction losses • Life is speed/size limited and is relatively short 	Not suitable due to $DN^{(a)}$ limitations and losses
	Labyrinth seals	<ul style="list-style-type: none"> • Low drag losses • Long life, not speed limited • One piece shaft 	<ul style="list-style-type: none"> • Complex, close tolerances • Possibly not adequate in pressure regimes involved 	Detailed design-analysis required to determine suitability
	Ferrofluid seals	<ul style="list-style-type: none"> • Positive • Relatively low drag • One piece shaft 	<ul style="list-style-type: none"> • Speed size limited • Life not demonstrated 	Promising further research required to develop and demonstrate large, long-life version
	Magnetic feed-through	<ul style="list-style-type: none"> • Positively-contained vacuum at any level • Provides shaft damping 	<ul style="list-style-type: none"> • Power losses (hysteresis and electromagnetic) • Complexity - two piece shaft additional support bearings • May be torque limited • Requires bearings on vacuum side 	Probably suitable at present SOA. Complexity, costs, losses must be traded off against windage losses - vacuum pump capacity.
	Mechanical feed-throughs, e.g. Harmonic drive Wobble drive	<ul style="list-style-type: none"> • Positive mechanically • Positive vacuum seal 	<ul style="list-style-type: none"> • Proliferation of bearings and single-point failure possibilities • Never scaled to high torques 	Probably not suitable due to cost, complexity, unreliability, etc.
	Self contained (motor-generator in vacuum)	<ul style="list-style-type: none"> • Only electric wires pass through vacuum wall 	<ul style="list-style-type: none"> • Severely speed limited due to motor/generator speed characteristics • Cannot be ganged together • Heat dissipation 	Might ultimately be suitable for transportation flywheels

(a) Diameter x rotational speed.

For the purpose of estimating windage losses fluid dynamic approximations can be made based upon empirical data such as, for example, reported in References 60 and 61.

In Table 3.7, it should be noted that as a consequence of the hermetic seal selection, a magnetic feedthrough has been recommended. This recommendation, originally given in Reference 51, is also carried over to the IUS application.

Frame and Support Structure. The support structure of a flywheel system exerts a critical influence on bearing life, erection costs, and system weight. In addition to manufacturing cost considerations, the flywheel frame should be light and stiff. The former property impacts the power-to-weight ratio of the system as well as foundation costs. The latter, stiffness, has a direct influence on alignment and, hence, bearing life and maintenance costs. Spacecraft precedents suggest the two major configurations considered in Table 3.8.

Summary Remarks. The results of the study of alternative inertial energy storage candidates are summarized in Table 3.9 for three implementation time frames. The near term (1976-1980) candidate is the one of most interest, since it represents a system that could be constructed with a minimum of new technology. The configuration of this near-term energy storage wheel is relatively clear except with regard to the feedthrough. A magnetic feedthrough for transmission of the power levels anticipated would be very costly both in terms of material and fabrication. Additional analysis and testing would be required to more fully evaluate rubbing seals and ferrofluid seals for the IUS application. For example, if multiple wheels are used, and if they are placed in a common vacuum system, only 1 or 2 seals are necessary. The losses associated with rubbing or hydrodynamic seals could be acceptable for such a high power system. Life-testing and detailed design analysis would be required before ferrofluid seals could be used with confidence in high "DN" (i.e., large bore, high rotational speed) applications. Advanced concepts such as circulating ferrofluid systems should be evaluated.

TABLE 3.8. CANDIDATE FRAME/SUPPORT STRUCTURE CONCEPTS FOR INERTIAL ENERGY STORAGE

Subsystem	Concept	Advantages	Disadvantages	Conclusion
Frame/support structure	Ring	<ul style="list-style-type: none"> • Easy assembly • Ease of maintenance (i.e., accessibility to life critical components) • Ease of alignment. • Vacuum housing nonstructural 	<ul style="list-style-type: none"> • Complex ring and two piece vacuum housing • Possible vacuum seal problems due to complex housing shape • Possibly heavier than <u>optimized</u> shell configuration 	Probably most cost effective in terms of maintenance and life-critical alignment
	Shell	<ul style="list-style-type: none"> • Simple, two-piece configuration • Higher potential rigidity per pound than ring • Round, flat vacuum seal 	<ul style="list-style-type: none"> • Alignment difficult and must be disturbed to gain access--high maintenance costs • Vacuum housing is structural 	Possible use for light, advanced system having low maintenance requirements inside vacuum housing

Evaluation of a Candidate Concept

Candidate Selection. A major difficulty of this study has been the lack of a precedent in detailed overall system design. The extensive experience in aerospace flywheels appears to be of little use in scaling up to the larger, multi-kilowatt hour and megawatt-hour units required for IUS generation. Consequently, in order to analyze and project costs and feasibility, it has been necessary to define or crudely design a system. That is, the results are based upon a relatively unrefined design and could be significantly modified in an intensive design/analysis exercise (outside the scope of the present study).

The concepts that are believed to be the most viable for three time frames have been previously summarized in Table 3.9. They represent a "best judgment" as to how the various systems should be configured on the basis of state of the art in the various subsystem areas.

In order to analyze the near-term concept in greater detail, it is necessary to make some design assumptions. These assumptions, and the rationale for each are summarized in Table 3.10.

A single-wheel, multirim configuration, should represent a concept that could be designed and manufactured within the framework of the current state of the art in material (metal and composites, such as fiberglass/epoxy), vacuum, and bearing technologies (some critical areas, which require further research and analysis, will be enumerated in detail later). Within these practical, real-world constraints it is likely that a flywheel of only modest capacity--a few hundred kWh--can be built. Thus, for application to even the smallest IUS requirements, more than one wheel is required. The concept that has been pursued is a multiple wheel array where more than one wheel is driven by a single motor-generator set. Previous experience⁽¹⁵⁾ has shown that a collinear arrangement, as shown schematically in Figure 3.1, is mechanically optimal.

TABLE 3.9. SUMMARY OF CANDIDATE INERTIAL ENERGY STORAGE CONCEPTS
FOR DIFFERENT IMPLEMENTATION TIME FRAMES

Subsystem	Criticality	Time Frame		
		Near Term, 1975-1980	Midterm, 1981-1985	Long term, 1986-1990
Flywheel	Cost critical	Multirim, composite metallic and nonmetallic materials	Multirim-higher strength and mass	Built-up super flywheel-composite construction-integral shaft
Motor/generator	Cost/performance critical	Variable frequency field machine	(Unknown)	(Unknown)
Speed reducer	Cost critical	Horizontal shaft, parallel off set transmission (off the shelf)	Refined, dedicated transmission design	Harmonic drive (Possible)
Bearings	Life and cost critical	Ball bearings with oil-misc lubrication	Magnetic-ball bearing hybrid	Magnetic-super conducting
Vacuum system	Cost-efficiency critical	For Hermetic system, using a magnetic feedthrough, turbopump	Turbopump	Cryopump plus mechanical pump
Seals/Feedthroughs	Life and cost critical	Magnetic feedthrough, possibly labyrinth seals	Ferrofluid seals	Harmonic drive (Possible)
Frame and support structure	Cost critical	Steel ring configuration Steel vacuum enclosure	Steel-composite ring Composite vacuum enclosure	Optimized composite shell configuration

TABLE 3.10. ASSUMPTIONS UNDERLYING AN INERTIAL ENERGY STORAGE CONCEPT FOR NEAR-TERM IUS APPLICATION

Assumed Parameter	Rationale	Comments
Maximum Wheel Diameter - 3.05m	<ul style="list-style-type: none"> • Ease of manufacturing 	<ul style="list-style-type: none"> • Larger wheels would have to be assembled and balanced at the site
Maximum Wheel Length - 3.05m	<ul style="list-style-type: none"> • Transport-clear bridges 	<ul style="list-style-type: none"> • Windage losses increase with V^4, optimum design might be smaller in diameter
Wheel speed - Maximum 10,000 rpm	<ul style="list-style-type: none"> • This diameter/speed ratio appears compatible with near-term materials • Electrical equipment limits the $\Delta(\text{speed})$ to 5,000 rpm. A nominal 5,000 rpm lower limit is desirable from lubrication standpoint. 	<ul style="list-style-type: none"> • Optimization would require detailed trade-off analysis
Energy storage speed range - 5,000 rpm	<ul style="list-style-type: none"> • 2:1 storage range is necessary with respect to power generating requirements 	<ul style="list-style-type: none"> • Optimization would require trade-off of rpm range versus variable-speed transmission economics
Charge-discharge time = 6 hours	<ul style="list-style-type: none"> • Compatible with system requirements 	<ul style="list-style-type: none"> • Optimization would require detailed trade-off with economics and system requirements

Note: Detailed design or trade-off analyses die outside scope of present study.

Technical Characteristics. A preliminary design study was carried out in which bearing fatigue life and energy storage capacity in terms of wheel mass and speed were traded off. As a result of that study, a single-wheel module design was evolved. This concept has the characteristics shown in Table 3.11.

For the IUS application, a 5-wheel array appears to be appropriate. This system would have the characteristics summarized in Table 3.12. Each of the factors in that table is discussed in the following paragraphs.

Round-Trip Efficiency. The round-trip efficiency of inertial energy storage devices will be bounded by the efficiency of the power conversion equipment which converts the mechanical energy stored in the rotating wheel into usable electrical power. Typical efficiency values for this equipment range from 88 to 90 percent. This would result in round-trip efficiencies on the order of 77 to 80 percent. In addition, the following factors will influence the determination of system efficiency during various periods of the storage cycle:

- Bearing losses
- Windage losses
- Transmission Efficiency
- Feedthrough/Seal losses.

Preliminary estimates of these factors indicate that overall round-trip efficiencies on the order of 60 to 70 percent should be achievable with inertial storage systems.

Energy Storage Density. The 5-wheel array may be modeled as a 2.4-m (8-ft) square rectangle, 13.7-m (45-ft) long; thus, the approximate volume excluding the generator, is approximately 79 m^3 (2790 ft^3). Allowing approximately 20 percent of this volume for the generator and power conditioning equipment brings the total volume to about 100 m^3 (3098 ft^3). Thus, the energy storage density for the system can be estimated as 15 kWh/m^3 (0.4 kWh/ft^3).

Charge/Discharge Characteristics. The charge/discharge rates are independent and largely a function of the capacity of the drive train (i.e., motor/generator and mechanical transmission). The design under consideration may be charged

TABLE 3.11. CHARACTERISTICS OF A NEAR-TERM SINGLE WHEEL

Wheel mass, kg	2,909
Wheel diameter, m	2
Maximum speed, rpm	10,000
Minimum speed, rpm	5,000
Speed range, rpm	5,000
Available energy, MJ	1.1×10^3
kWh	294
Charge/discharge time, hr	6
Power level, kW	50
Nominal	
Bearing fatigue life AFBMA ^(a) , hr	7,150
Advanced bearing life, hr	50,000

(a) AFBMA - American Friction Bearing
Manufacturers Association

TABLE 3.12. TECHNICAL CHARACTERIZATION OF A NEAR-TERM INERTIAL ENERGY STORAGE CONCEPT FOR IUS APPLICATION

Energy Storage Concept	Power kW	Storage Capacity (a) kW	Round-trip Efficiency, Percent		Energy Storage Density, kW/m ³ DE	Useful Life, year		Maximum Charging Rate, kW		Maximum Discharge Rate, kW	
			N _t			L		R _c		R _d	
			High	Low		High	Low	High	Low	High	Low
			High	Low		High	Low	High	Low	High	Low
5-Wheel	250	1500	70	60	15	50	10	1500		1500	

and discharged in 6-hour cycles. A larger (and more costly) drive train would allow shorter cycles, with one hour as a practical limit.

Hardware Availability. Although the candidate concept is essentially state of the art in materials and components, the hardware are not off-the-shelf items as such. Thus, delivery lead times of at least 1 to 2 years can be anticipated.

Transportability. The modularity of the equipment should permit common-carrier transport from factory to the IUS site. The wheels can be shaft-mounted at the factory. As a precaution to prevent brinelling of bearings, those components should be shipped unmounted and installed on site. The protective containment (see subsequent discussions of Safety Considerations) would, of course, be constructed on-site.

Operational Availability/Reliability/Maintainability. The inertial energy storage concept as proposed for the IUS is mechanically simple and thus should not pose unusual maintenance accessibility. However, as with any rotating machinery possessing large amounts of inertial energy/angular momentum, careful monitoring of balance and bearings will be required. Lack of experience with the multirim wheel will clearly dominate the initial philosophy of periodic inspection.

Useful Life. The inertial energy storage system does not have a definite life in terms of the point at which the entire unit is scrap. Each component has a finite and different service life ranging from 1 year for the bearings to over 20 years for the flywheel itself. Since the wheel is the most costly single component, the service life of the system is expressed in terms of that of the wheel.

Safety. Several potential safety problems have been identified that are believed to require consideration. Three major catastrophic failure modes, which probably dominate, are outlined in Table 3.13 along with effects and possible safeguards.

TABLE 3.13. INERTIAL ENERGY STORAGE SAFETY CONSIDERATIONS IN TERMS OF MAJOR CATASTROPHIC FAILURE MODES

Potential Catastrophic Failure Mode	Primary Effects	Secondary Effects	Potential Safeguards
Wheel disintegration	Sudden release of stored energy. Transfer to container, building, etc.	<ul style="list-style-type: none"> • Destruction of vacuum container-implosion • Heavy building damage, hazard potential over a considerable radius • Domino effect on other wheels in array 	<ul style="list-style-type: none"> • Tarped earth bunkers with lids of concrete and clay or water tanks • A brush-type wheel minimizes this hazard • Domino effect minimized by break-away couplings and carbon vacuum system: windage automatically stops array in event of vacuum failure.
Bearing failure	Conversion of kinetic energy into heat at bearings over a period of minutes to hours. Total destruction of bearings.	<ul style="list-style-type: none"> • Extreme heat-fire hazard • Damage to trunnions • Shaft breakage 	<ul style="list-style-type: none"> • Fire hazard minimized by CO₂ flood provisions or H₂O deluge from water tank lid • Temperature rise monitors and shut-off provisions, back fill of vacuum enclosure with CO₂ would be a good brake
Implosion or fast vacuum leak	Collapse of vacuum enclosure. Relatively rapid pressure rise.	<ul style="list-style-type: none"> • Damage to wheel from enclosure • Damage to system by shock wave 	<ul style="list-style-type: none"> • Wheels will stop quickly due to pressure loss • This contingency is best prevented by inspection

It is believed that the inertial energy storage system can be made relatively safe by placing the entire system in an underground trench having relatively thin concrete walls backed with tamped earth. Lids could be made from reinforced concrete boxes filled with either clay or water. The bunker should be floodable with water or CO_2 in the event of a fire. The vacuum container should also be capable of relatively rapid back fill with CO_2 as an emergency brake.

Expansion Capability. An IUS installation's inertial energy storage capacity could be expanded readily in the same sense that a utility generating station's peaking capacity can be expanded by the addition of self-contained gas turbine/generator "modules". Since the addition would probably not be housed in the same building as the baseload generating units, it is presumed that land surface would be available at the IUS station site.

Environmental Concerns. Among the various environmental concerns (i.e., air and water quality control, noise abatement, and land use policy), only noise is of inherent significance. With the containment shielding in operation position, it is expected that sufficient attenuation could be obtained.

Cost Characteristics. Since a large inertial energy storage system has never been designed, and since the present analyses are based upon a single preliminary design concept, cost estimates are relatively crude. The cost characteristics are summarized in Table 3.14. The cost rationale for (1) the flywheel, and (2) support hardware electric equipment, installation and maintenance, are discussed in the following paragraphs.

Energy Storage Wheel Costs. The projection of realistic values for cost of composite materials applied to energy storage wheel design is difficult to solve without an extensive techno-economic impact study. Most cost projections are unrealistic in their assumption of simultaneous breakthroughs in several civil markets. It is also assumed that progress in conventional materials will be limited. However, while there have been a large number of experimental exploratory commercial applications of composites, two of the principal production items that have been commercialized are golf clubs shafts and the

TABLE 3.14. FIRST COST COSTS FOR 1500 kWh, 5-WHEEL
ENERGY STORAGE SYSTEM

Subsystem	Cost (thousands of \$)
Wheels	150-450
Transmission	9.6
Mechanical hardware	86.0
Bearings	20.0
Electrical equipment	14.6
Balance of plant	15.1
Installation	3.2
Vault, pad, building	55.6
Maintenance (annual)	23.0

selective reinforcement of fiberglass or Kevlar reinforced plastic kayaks⁽⁶²⁾. There is no clear indication at present that advanced composites will expand beyond the category of being classified as specialty materials.

It does not seem possible to forecast accurately the cost reductions that can be achieved with composite materials. This is not only because of the preceding considerations, but because of improvements being made with conventional materials, fabrication and joining processes, and design concepts that are continuously under development to upgrade the efficiency of application of metals (e.g., steel and titanium). While there was initially a drastic reduction in the cost of advanced fibers from several hundred dollars per unit weight to the present prices, there do not appear to be any reliable indicators with fibrous composites. The total costs involved in fabricating composite hardware meeting aerospace level specifications must also be taken into account. That is, the cost of fabrication must include tooling, quality assurance (QA) and nondestructive testing (NDT) costs.

Keeping these limitations in mind, a range of \$100 to \$300 per kWh has been selected to represent the cost of the fabricated wheel. These costs are based on a review of the possible materials and fabrication methods employed, and should be considered as optimistic and conservative figures, respectively.

Mechanical Hardware Costs. The mechanical transmission is easiest to cost, since a nominally off-the-shelf design is adequate. An estimate from a leading gear company indicates a transmission for the five wheel system will cost approximately \$9,600.

The support ring, shaft (but not wheel), bearing, lubricant system, vacuum enclosure and coupling cannot be costed since detailed designs have not been made. Consequently, a unit cost has been used based upon cost per unit weight for precision machine tools. It is concluded that this hardware should cost approximately \$6.00/kg as of 12/75*. It is believed that this figure is fairly

* This value is based upon the analyses described in Reference 51, inflated by the wholesale price index increment from 1/75 to 12/75.

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accurate, and also that further cost oriented design could reduce this to \$4.40/kg in quantities of 500-1000 units. The design under study has been configured with low cost, relatively high volume, manufacture in mind. No special tooling or significant capital expense is involved in fabricating the shafts, rings, and housings. Shops capable of building these are widespread in the United States. Likewise, the bearings, although made of a special steel*, can be manufactured by at least three major U.S bearing companies.

Fabrication/Erection Costs. It is anticipated that the first generation IUS installations would be erected on site. In order to eliminate shipping damage to the life-critical spin-axis bearings, the wheel/shaft assembly would be shipped separately from the ring support assembly. Erection would consist of emplacement of the support ring and lower vacuum shroud, installation of the bearing cartridges on the spin shafts, installation of the spin axis in the support ring, installation of the upper vacuum shroud and alignment of the array by laser bore sighting. The costs for this operation are believed to be similar to those associated with a large steam turbine--i.e., \$2.12/kWh.

Maintenance Costs. Major maintenance will probably be confined to the following components:

- o Mechanical transmission
- o Spin axis bearings
- o Feedthrough.

Preliminary analyses indicate that the bearings should last reliably for about 1 year (advanced bearings will run approximately 20x longer). Replacement involves removal of the shroud, uncoupling the individual wheel from its neighbors, lifting the wheel from its trunnions, replacing the bearings, reassembling and realignment. The time required to replace the spin axis bearings is approximately half that required to erect the flywheel, or approximately \$23,000 for labor and materials. As the price of bearings comes down and the fatigue life is increased, this cost should be substantially reduced to approximately \$2000/year.

* Ultraclean M-50.

The feedthrough maintenance costs are undetermined, since this critical component is not defined. With 1-2 feedthrough per unit, replacement time (including alignment) should not exceed 2 days.

The transmission should function for 10 years between overhauls. An annual oil change would probably be desirable.

Installed Costs for IUS Application. The cost estimates developed above are based on an assumed 5 wheel energy storage module with an energy storage capacity of 1500 kWh. Application of inertial energy storage systems to IUS will require a number of these or similar modules depending on the particular installation. In order to simplify the estimation of installed costs for IUS application, it is desirable to express the costs of these storage systems on a unit basis via the following equation

$$C_T = C_S (\text{Capacity Required}) + C_P (\text{Power Required})$$

where

C_T = installed cost of energy storage system, \$

C_S = storage related capital costs, \$/kWh

C_P = power related capital costs, \$/kW

Using the costs generated for the 5 wheel baseline, the cost coefficients can be calculated as

$$C_S = \$210 - 410/\text{kWh}$$

$$C_P = \$157/\text{kW}$$

These factors were utilized in calculating cost estimates for flywheel systems which would be required for the various IUS baselines. The results are presented in Table 3.15. It should be pointed out that the values reported in this table are based on the peak output power required during the discharge cycle.

TABLE 3.15. SUMMARY OF INSTALLED COSTS OF INERTIAL ENERGY
STORAGE FOR IUS APPLICATIONS

IUS Application	No. of Base Load Diesel Electric Generators	Energy Stored, kWh	Peak Power Required, kW	Cost Per Unit Power at Peak Requirement' \$/kW
1000-Unit Apartment	5	1056	374	749-1313
	4	4065	905	1100-1998
Village Complex	7	3175	2921	385-603
	6	33,638	7696	1025-1949

Research and Development Opportunities

With regard to the process of applying new materials to hardware, it is considered important to realistically assess the time-span required. The difficulties involved in transferring emerging materials technologies to hardware that achieves production status, should not be underestimated. One example is the time taken to develop glass-reinforced plastic (GRP) primary structures for aircraft. The first significant application of GRP to aircraft primary structures in the United States was the fuselage of the Vultee BT-15, a single-engined, low-wing monoplane which was designed, fabricated, and tested in the laboratory in 1943 by the United States Air Force (USAF). The first flight of this BT-15 was in March, 1944. On a strength-to-weight basis, this sandwich fuselage, with GRP skins and an end-grain balsa core, showed an improvement of 50 percent over the aluminum structure. Around the same time, the USAF designed and fabricated a wing for the North American AT-6, also a single-engined, low-wing monoplane. This structure was also of sandwich design, but utilized GRP skins and a cellular cellulose acetate core. However, 25 years elapsed before the first flight of the four-seater Windecker "Eagle", which had 80 percent of the structure in GRP. It is therefore essential, when evaluating candidate materials, processes, and concepts, to consider realistic time lags that may occur before a new technology is committed to production.

The development of large flywheel energy-storage systems requires that research and development in critical areas be carried out on a broad front with a systems perspective. Accordingly, general recommendations can be outlined as follows.

- Perform R&D on flywheel material systems:
 - Conduct a techno-economic forecast on advanced composite materials to determine realistic values for future fiber costs.
 - Develop multi-rim and constant stress conceptual designs which cost-effectively employ material systems in metals and composites with regard to fabrication cost, materials, utilization, fracture tolerance, and the life-cycle.

- o Develop a computer program for analysis and optimization of composite and metallic material systems for flywheels to achieve efficient material utilization. Conduct trade-offs with fabrication cost.
- o Develop automated monitoring methods of quality assurance and nondestructive testing for fabrication and operation of flywheels.
- o Conduct cost-effective analysis based on systems life-cycle of hybridized multi-rim and constant stress flywheels.
- o Develop conceptual designs of advanced composite shafts efficiently integrated with composite flywheel designs.
- o Develop cost-competitive fabrication methods for flywheel shafts.
- Perform R&D on two major life/cost critical subsystems, viz.,
 - o Spin axis bearings
 - o Feedthrough and/or seals
- Develop high-capacity, low drag bearings through research in the following areas:
 - o Improved ball bearings
 - o Hybrid-ball/magnetic bearings
 - o Magnetic bearings - especially superconducting
- Develop long life, efficient feedthroughs:
 - o Heavy-duty magnetic couplings
 - o Long-life ferrofluid seals
 - o Advanced low drag rubbing seals
- Develop means for efficiently generating electric power with speed ranges in excess of 5000 rpm that would allow higher storage density wheels.

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4. SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Basic Aspects of Superconducting Magnetic Energy Storage

Under "normal" (i.e., not superconducting) circumstances, there are two basic methods of storing electromagnetic energy, viz,

- In the dielectric medium of a capacitor through the creation of an electric field
- In the permeable medium of an inductor through the creation of a magnetic field.

In recent years the development of normal capacitive and inductive devices capable of storing multimegajoules of energy has been motivated by requirements for pulsed power delivery, i.e., energy transfers effected in the sub-microsecond regime^(1,2,3). No corresponding development has occurred for the expressed purpose of large-scale energy storage, because the economics relative to other forms of energy storage appeared unattractive. No technical breakthroughs have become evident that would ease the situation for capacitive energy storage; but, the development of the superconducting magnet has heralded a promising possibility for large-scale inductive energy storage.

Before proceeding to a discussion of the physical aspects of superconducting magnetic energy storage, some commentary is warranted on the literature and ongoing investigations. It can be readily observed that the literature on superconductors and devices is rapidly growing. References 4-28 represent a wide assortment of the open literature, while References 29-44 are more directly concerned with energy storage aspects. In these citations the various technical and economic aspects of superconducting magnet design, fabrication, and operation are addressed.

Two groups have reported much of the recent R&D on superconducting magnetic energy storage in the USA; they are located at the Los Alamos Scientific Laboratory (LASL) and at the University of Wisconsin. The principal contributions of the LASL group have been in the study of the economics of superconducting magnetic energy storage and the advancement of laboratory

scale devices from 10 kJ (2.3×10^{-3} kWh) by several orders of magnitude to 100 MJ (2.3×10^{-2} MWh). Thus, they have come to grips with the practical problems of scaling to larger capacities. The University of Wisconsin group has concentrated its efforts on very large capacity (36×10^6 MJ (10,000 MWh)) concepts.

The physical basis for the superconducting magnet lies in: (1) the immeasurably low electrical resistance of a superconductor; and (2) the practically complete exclusion of magnetic flux from the interior of a superconductor (Meissner effect). These phenomena are, of course, the consequences of the superconducting state, a thermodynamic domain allowable for certain materials. This domain is characterized and bounded by three parameters.

- Critical temperature, T_c
- Critical magnetic field strength, H_c
- Critical electric current density, J_c .

That is, for a material capable of undergoing transition from a "normal" to a superconducting state, the achievement and maintenance of the latter depends upon (T, H, J) remaining below their critical values. Nominal critical values for two niobium alloys (niobium-titanium and niobium-tin) that are presently in use for superconducting magnets are shown in Table 4.1. The low critical temperatures clearly require cryogenic refrigeration.

It is evident that the reduction of resistance to nearly zero practically eliminates the ohmic (I^2R) power dissipation. In other words, once the current circulation in the superconducting magnet is established in the "persistent" mode, no additional power transmission to the magnet is required. This gives rise to a basic economic trade-off, viz, the savings gained by a superconducting magnet from elimination of wasted power versus the cost of special materials and special refrigeration.

Much of the interest in superconducting magnets has been in the attainment of high magnetic field strengths. From elementary electromagnetics, it is known that for a given magnet configuration,

$$(\text{Field strength}) \propto (\text{Current density}).$$

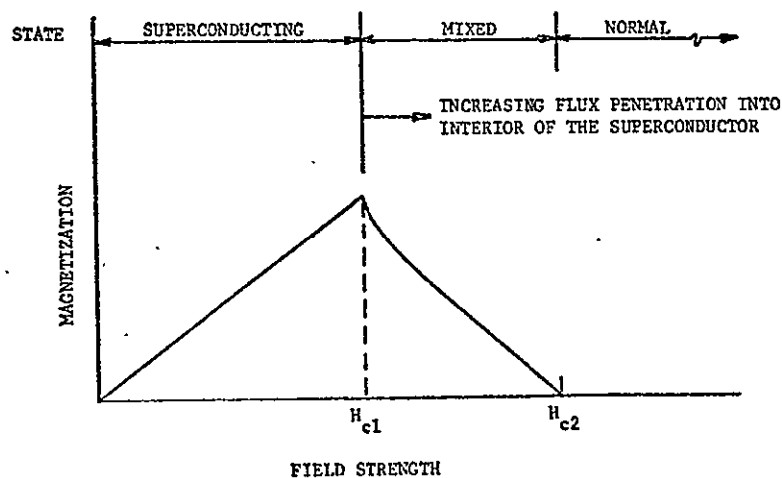
But, it is also true that

TABLE 4.1. CRITICAL VALUES FOR SUPERCONDUCTOR MATERIALS

Material	Critical Temperature ^(a) , T_c - deg K	Critical Magnetic Field Strength ^(b) , H_{c2} - kG(c)	Critical Electric Current Density ^(b) , J_c - A/m ²
Niobium, 48 percent Titanium (NbTi)	10.2	120	5×10^9 (d)
Niobium Tin (Nb ₃ Sn)	18.3	220	3×10^9 (e)

Source: Tabulation in Reference 4.

- (a) For reference purposes, liquid helium temperature is 4.2 deg K and liquid hydrogen temperature is 20 deg K.
- (b) At liquid helium temperature.
- (c) H_{c2} is the upper critical field strength as indicated in the magnetization curve sketched below.
- (d) At 50 kG.
- (e) At 100 kG



- (Energy stored per unit volume of the magnetic field) is proportional to (Field strength)² and, therefore, is proportional to (Current density)².

The implication here is that advances in high field superconducting magnet technology should provide helpful ideas for storage. Of course, it also means that the problem areas are also shared--as will be indicated in the following discussions of: quenching, magnetic stresses, magnetic shielding, joints and leads, and interfacing with the "normal" components.

An interesting operational problem is posed by the possibility of an uncontrolled transition reversal from the superconducting state to normal, i.e., "quenching", that results in an ohmic power pulse dissipation into the cryogenic refrigerant. This instability can originate locally during charge up of the magnet and cascade rapidly through the windings. The potential hazard associated with vaporization of the refrigerant is partially relieved by: (1) the present fabrication practice of embedding the superconducting material filaments in a stabilizing material that is a good heat sink (usually copper); and (2) the presence of additional heat sink capacity in the reinforcement structure.

Another interesting consideration arises from the fact that a stress is created in the superconductor by the body forces exerted on the magnet windings.

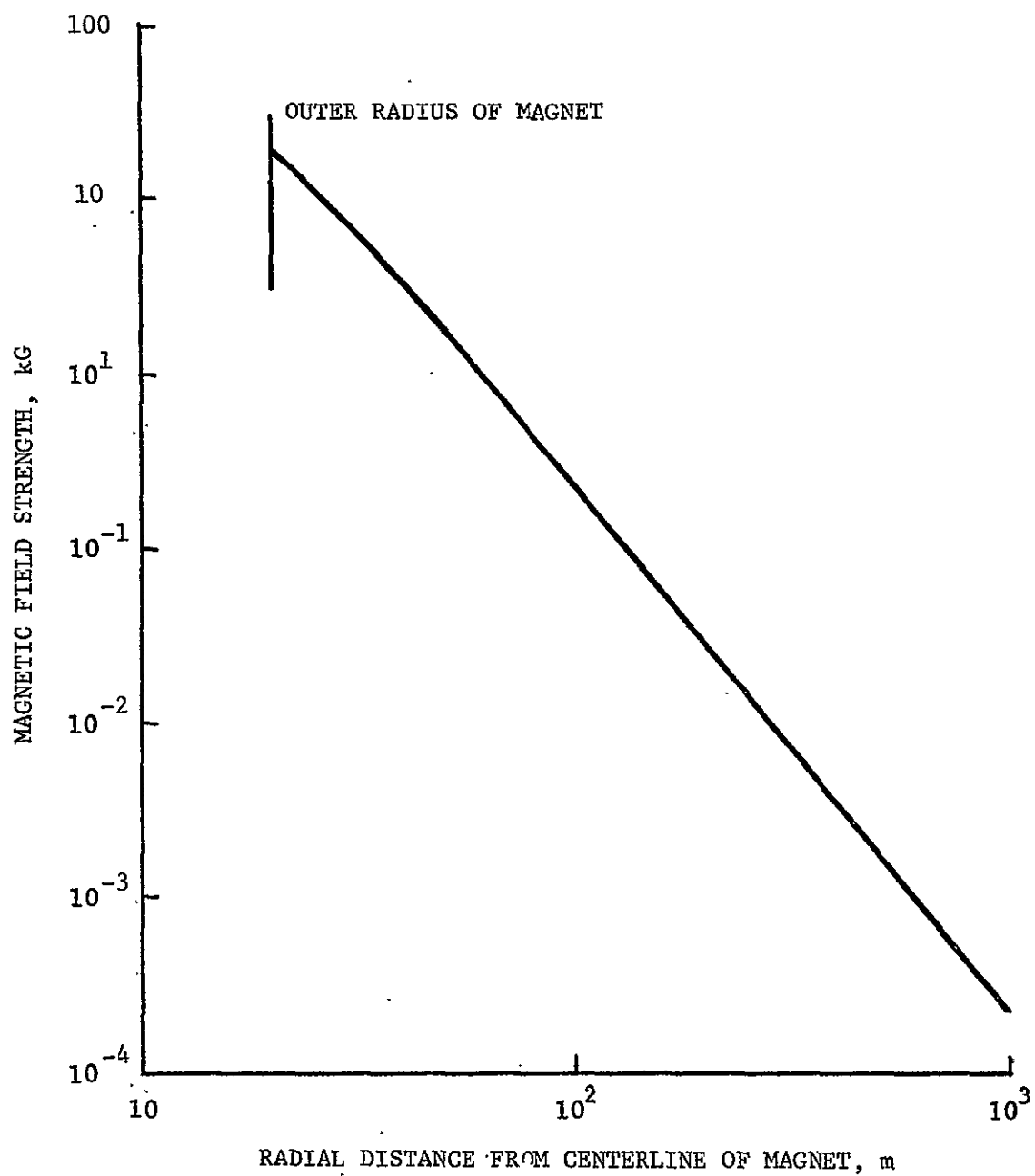
Since,

- Magnetic force is proportional to electromagnetic (Field strength)² and, therefore, is proportional to (Current density)²,

it can be seen that high current densities achievable with superconductors are accompanied by high force levels that could cause localized failure and subsequent shorting.

Yet another facet of the superconducting magnet is the possible requirement for shielding. The extent of a field surrounding a solenoidal magnet is illustrated in Figure 4.1, which indicates the radial decay for a 30 m (98 ft) diameter magnet storing 2.2×10^6 MJ (611 MWh) at 100 kG. Magnetic shielding may be required to protect both people and equipment.*

*Standards for the protection of people have not been established at the present time; see also value point discussions on safety considerations.



Plotted from data in Reference 37.

FIGURE 4.1. MAGNETIC FIELD DISTRIBUTION EXTERNAL FROM A 30-M DIAMETER MAGNET ENERGIZED AT 100 KG

Suitable methods must be devised for making zero-resistance or superconductive joints between sections of superconductor. A joint of resistance as small as 1 microhm would dissipate energy at a considerable rate. Over an 8-hour period this would represent a negligible loss of energy in comparison with the storage capacity but the local heating effect could result in serious instability. It is also apparent that careful attention must be given to the design of the "persistence switch" as that disconnects the magnet from the power source once persistent current circulation of the desired level has been established. A wholly satisfactory switch does not yet exist. A primary need for persistent mode operation results from protection afforded the inverter portion of the power conditioning equipment. Present day inverters are not capable of handling the high currents of normal mode of operation.

Leads must also be designed for high power transfer into and out of the coil and its surrounding dewar. Since the power source for charging the superconducting magnetic energy device is AC, there is need for an inverter/converter arrangement. Considerable attention has been given to this aspect of interfacing equipment (e.g., Reference 41).

Alternative Approaches for Implementation

There are relatively few design variables from which to form combinations to represent different candidate concepts for superconducting magnetic energy storage. These variables are

- Coil (magnet) shape
- Superconductor material/fabricated element arrangement
- Refrigeration equipment
- Support structure arrangement, i.e., "reinforcement"
- Power conditioning equipment.

Magnet Shape. There are a number of magnet shapes formed by conductor winding(s) that have been studied in the past in an effort to derive a desired magnetic field distribution. These include the solenoid, the toroidal, and the so-called Brooks coil. The principal merits of the solenoidal winding are simple fabrication and efficient volumetric use of

the conductor. Its major drawback is low energy volumetric density. The toroidal shape possess the advantage that the magnetic field is within the coils and nonexternal. The Brooks coil is configured specifically to maximize the amount of stored energy for a given amount of superconductor winding.

Superconductor Material/Fabricated Element Arrangement. With regard to superconductor material, the choice at the present is between the niobium-titanium and the niobium-tin alloys. The former has a lower critical temperature (see Table 4.1) but is not as brittle as the latter. On the basis of a greater experience base and somewhat lower cost, the niobium-titanium (NbTi) fiber/copper matrix composite "tape" presents a more attractive choice.

Refrigeration Equipment. There is no choice but to use a liquid helium refrigeration system. There is greater latitude with regard to dewar configuration.

Support Structure Arrangement. As previously discussed, high strength magnets can develop very high stress levels in the windings. Then, mechanical support structure, or "reinforcement" will compete with refrigeration for space adjacent to the superconductor windings. "Cold reinforcement" results if the support structure is immersed in the refrigerant, that is, contained within the dewar. "Warm reinforcement" results if the structure can be assembled external to the refrigerant, that is, outside the dewar. The latter arrangement can be much less expensive than the former--especially for large size installations (the differential becomes less significant for smaller size magnets); the IUS installation is considered "small" compared to utility applications. The choice of reinforcement type also leads to a consideration of above vs. underground installation. A warm reinforcement design would suggest using the compressive strength of rock to advantage in supporting the reinforcement structure in an underground installation. However, this choice is not without problems, because the low tensile strength of rock could lead to extensive radial cracking--say 10 times the magnet radius. This problem is alleviated by excavating to greater depths to

capitalize on overburden pressure. Additionally, the low elastic modulus of rock suggests (as it did to the University of Wisconsin investigators) a fluid separator between the dewar and the excavated chamber walls.

Power Conditioning Equipment. Here again, as in the case of refrigeration equipment, there is no choice but to provide interfacing equipment between the dc superconducting magnet and the ac main IUS power bus. Options do exist for the electrical designs with regard to implementation. Thus, depending upon the current density regime--there are a variety of options. A typical arrangement is shown in Figure 4.2.

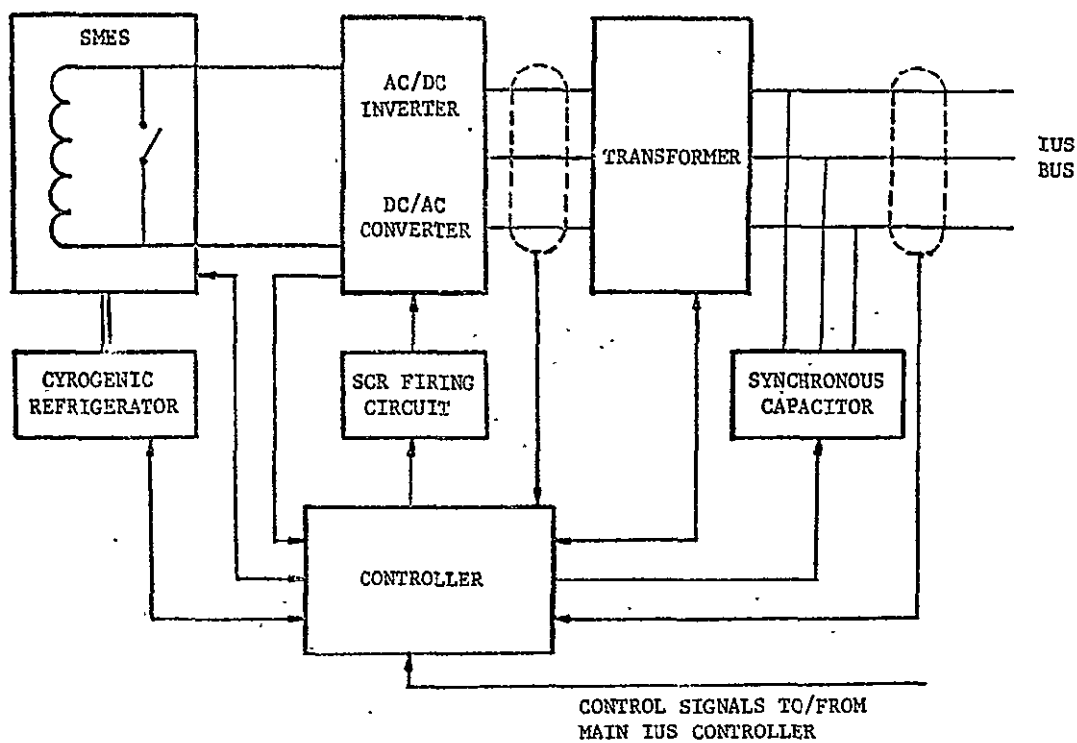
Evaluation of a Candidate Concept

Candidate Selection. The solenoid configuration was chosen for the superconducting coil. According to the work performed at Los Alamos Scientific Lab (LASL) ⁽³⁷⁾ a solenoidal winding is the most economical for coils smaller than 10-MWh capacity. The material selected is the niobium-tin (Nb-50 wt% Ti)/copper matrix composite in a "tape" arrangement suitable for winding.

For the IUS application, it appears that an above ground cold reinforcement installation would be the most practical approach. This choice is also based upon Reference 37, which indicates cold reinforcement is economical for coils of less than 10-MWh capacity.

Technical Characteristics. Although a design study was not undertaken for the candidate superconducting magnetic energy storage concept, a number of technical characteristics were examined to afford a general characterization of the device. These characteristics include

- Round trip efficiency
- Charge/hold/discharge capabilities
- Energy storage density
- Hardware availability
- Transportability
- Operational availability/reliability/maintainability



After Reference 37

FIGURE 4.2. EXAMPLE ARRANGEMENT OF POWER CONDITIONING EQUIPMENT

- Useful life
- Safety considerations
- Expansion capability
- Environmental concerns.

Round-Trip Efficiency. Estimates have been made of the round trip efficiencies associated with the three design point conditions

- 1000-Unit Apt Complex - 5 baseload diesel electric (DE) generators (i.e., 1 set replaced by energy storage unit)
- 1000-Unit Apt Complex - 4 baseload units (i.e., 2 DE units replaced)
- Village Complex - 6 baseload units (i.e., 2 DE units replaced).

The major loss mechanism affecting round trip efficiency would be refrigeration losses (during discharge). It has been estimated that these losses are approximately as follows:

<u>Energy Storage Capacity, kWh</u>	<u>Refrigeration Losses, kWh/h</u>
1,000	2
40,000	60

A power converter efficiency of 98 percent is assumed, and a depth of discharge not exceeding 75 percent of rated capacity is also assumed. The results indicate round trip efficiencies on the order of 90 percent, a value which has been adopted to represent fully developed superconductor magnetic energy storage performance.

Charge/Hold/Discharge Capabilities. There is no practical rate of charge limitation on the superconducting magnet field. The limitation will be imposed by the transfer capabilities of the power conditioning equipment and the withdrawal rates from the IUS bus or available off-peak power. If the magnet power conditioning unit must be rated for maximum power levels of the IUS there are no problems. Once the superconducting coil is operating in the persistent mode, i.e., holding without additional power input, the losses are negligibly small.

Energy Storage Density. The significance of energy storage density (volumetric basis) here is somewhat obscured by the wide variations in plant dimensions that would arise from the design of the dewar and reinforcement structure. Values in the range $18\text{--}35 \text{ kWh/m}^3$ ($0.5\text{--}1 \text{ kWh/Ft}^3$) such as listed in Reference 46 are thought to be as indicative of preliminary design as any other estimates.

Hardware Availability. Neither design nor basic hardware for a superconducting magnetic energy storage installation in an IUS are "off-the-shelf". As a matter for consideration, the introduction of such units in even modest numbers may have to contend with the limited availability of superconductor material, most of which is presently used in magnets for high energy physics and fusion studies.

Transportability. It is unlikely that completely assembled solenoids would be transported to the installation site. Instead, "pancakes" would be wound and the stack assembled on site. Similarly, the dewar would be field erected.

Operational Availability/Reliability/Maintainability. Lacking the precedence of an operating prototype, it is suggested that energy storage superconducting magnets should exhibit availability/reliability/maintainability behavior similar to other high field superconducting magnets now in use. Thoughtful design, careful fabrication, inspection, and assembly--including adequate shock/vibration isolation--and rigorous refrigeration equipment maintenance should minimize unit down time.

Useful Life. Projections for useful life of a superconducting magnetic energy storage installation suggested in a previous study⁽⁴³⁾ are in the range 20-30 years.

Safety Considerations. There are several aspects of operational safety that are immediately apparent: (1) consequences of superconductor quenching, (2) seismic protection, and (3) magnetic field exposure hazards to personnel. It was previously mentioned that the primary consequence of quenching would

be the rapid transfer of energy to the refrigerant that could result in an explosive vaporization. Since the dewar would not be constructed as a pressure vessel, perhaps an appropriate solution is a combination of provisions for adequate pressure relief and structural heat sink capability. Deliberate quenching has been studied on a small scale without catastrophic results.

Seismic protection is both an operational as well as a safety concern, because the superconducting magnet is sensitive to relative motion between adjacent superconductor segments. The safety aspect arises more from maintaining the integrity of the dewar.

With regard to biological hazards associated with exposure to dc magnetic fields, there are as yet no applicable standards (e.g., as might be set by OSHA) in force. The topic is currently being researched (e.g., Reference 45). There will be an inherent form of shielding protection owing to the necessity for guarding nearby control equipment from magnetic field transients during charge/discharge.

Expansion Capability. Once a superconducting magnetic energy storage device has been installed, it has in essence become a self-contained module and is not amenable to physical alteration. Thus, it has no expansion capability except in the sense of adding another "module".

Environmental Concerns. The superconducting magnetic energy storage method appears to present minimal environmental concern, because it and its refrigeration equipment are self contained. The question of magnetic radiation which has been previously addressed is a possible exception. If underground excavation is contemplated, then relief from architectural aesthetics is traded off for careful examination of possible interference with other underground resources and activities.

Cost Characteristics. As previously discussed, the suggested candidate for superconducting magnetic energy storage application to the IUS would embody solenoidal magnet geometry and cold (structural) reinforcement. In the following discussion estimates of the costs for such a concept are derived by scaling down information for larger hypothetical installations.

The reference cost data, taken from Reference 37, are given in Table 4.2 for three levels of energy storage capacity that range over several orders of magnitude. These data allow extrapolation to smaller energy storage capacities. The cost estimates for IUS study cases in which baseload generating units are replaced by superconducting magnetic energy storage devices* are summarized in Table 4.3.

Opportunities for Research and Development

Superconducting magnetic energy storage is believed to have significant potential for complementing baseload electrical generating equipment over a broad range of energy storage capacity requirements. Perhaps the most practical approach to long term development of this technique would be to support a gradual buildup of installed energy storage capacities. Such an evolution would tend to establish and maintain a developmental cost framework that would be reasonable.

Because IUS applications are considerably smaller in scale than those envisioned for large electric utilities, they offer an excellent opportunity for implementing the suggested development strategy. For example, there has been some concern regarding the practicality of constructing the very large magnets that would be required for electric utility installations. It would seem that IUS requirements would be a less distant extrapolation from the successful 12-meter bore magnets presently used for bubble chambers in high energy physics experimentation. There are two areas of interest over which

* A round trip efficiency of 90 percent has been assumed. The significance of this assumption is discussed in Volume II of the report.

TABLE 4.2. COST OF LARGE SMES SYSTEM HAVING SOLENOIDAL GEOMETRY

Subsystem and Cost, \$/kWh	Maximum Stored Energy, kWh		
	8.33×10^3	8.33×10^5	1×10^7
Superconductor	144.1	14	13
Dewar	324.1	36	36.9
Structure	96.0	(a)	(a)
Refrigerator	20.4	5.4	1.1
Converter	12.0	1.1	4.1
Miscellaneous ^(b)	<u>60.0</u>	<u>5.6</u>	<u>5.4</u>
SMES System	656.6	62.1	60.5

Notes: Data from References 37, 39, and 43.

Round trip efficiency = 90 percent

75 percent depth of discharge

(a) Included in Dewar Cost.

(b) Space, assembly, etc.

TABLE 4.3. COST OF SMES SYSTEM FOR IUS APPLICATION

Subsystem and Cost, \$/kWh	Maximum Stored Energy, kWh		
	1,000	4,000	35,000
Superconductor	245.0	177.0	66.0
Dewar and Structure	640.0	480.0	205.0
Refrigerator	31.5	23.5	15.5
Converter	15.7	13.3	10.2
Miscellaneous	<u>82.0</u>	<u>67.0</u>	<u>42.0</u>
SMES System	1014.2	760.8	338.7

developers of superconducting magnetic energy storage devices should maintain surveillance.

- Large magnet design/fabrication/operating experience associated with controlled thermonuclear research
- Availability (i.e., supply/demand behavior; see Reference 47) of the natural resources associated with superconductor fabrication.

Finally, the complex interactions of design factors leading to the integration of magnet shape, refrigeration containment/circulation, mechanical support, and interfacing with "normal" electrical equipment makes total system considerations of utmost importance. A number of these design factors will need continuing attention, e.g., (1) allowance for differential contraction during cool down to cryogenic refrigeration temperatures, (2) thermal stress cycling effects, (3) efficient structural design for magnet reinforcement, (4) allowable heat leakage, (5) low temperature electrical insulation, and (6) acceptable electrical safety.

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5. ELECTROCHEMICAL ENERGY STORAGE

Basic Aspects of Electrochemical Energy Storage

An electrochemical energy storage (E/S) installation for IUS application would consist of (1) power conditioning equipment and (2) rechargeable batteries arrayed as the energy storage device. A conceptual block diagram of such an arrangement is shown in Figure 5.1.

Available excess electrical energy from the IUS baseload generators would be stored during the charging portion of the E/S duty cycle. The storage mechanism is one of causing the battery's "active" materials (embodied in the traditional electrolyte and electrodes) to undergo chemical change. These materials are selected for ability to maintain a metastable chemical state; that is, the rate of self-discharge* is sufficiently small to allow the charging source to be disconnected if desired. During discharge the active materials revert to their stable states.

The number of charge/discharge cycles performed before power output declines to an unsatisfactory level constitutes the cycle life of the battery. Cycle life depends upon numerous factors, including (1) operating temperature, (2) rates of charge/discharge, and (3) depths of discharge. Depth of discharge refers to the proportion of active materials utilized during withdrawal of stored energy. Cycle life is favored by (1) low operating temperatures, (2) low rates of charge/discharge, and (3) shallow depths of discharge. Operating temperatures are inherent in the choice of active materials; rates of charge/discharge are governed by duty cycles; reduced depths of discharge can be, in effect, achieved with weight/volume/cost penalties by increasing the amount of active materials.

As indicated in Figure 5.1, power conditioning equipment is required to interface the DC battery with the AC bus IUS. Briefly, the functional requirements and equipment include the following:

* Self-discharge is an internal loss mechanism analogous to windage/bearing losses for inertial E/S and to the extremely small I^2R losses for SMES.

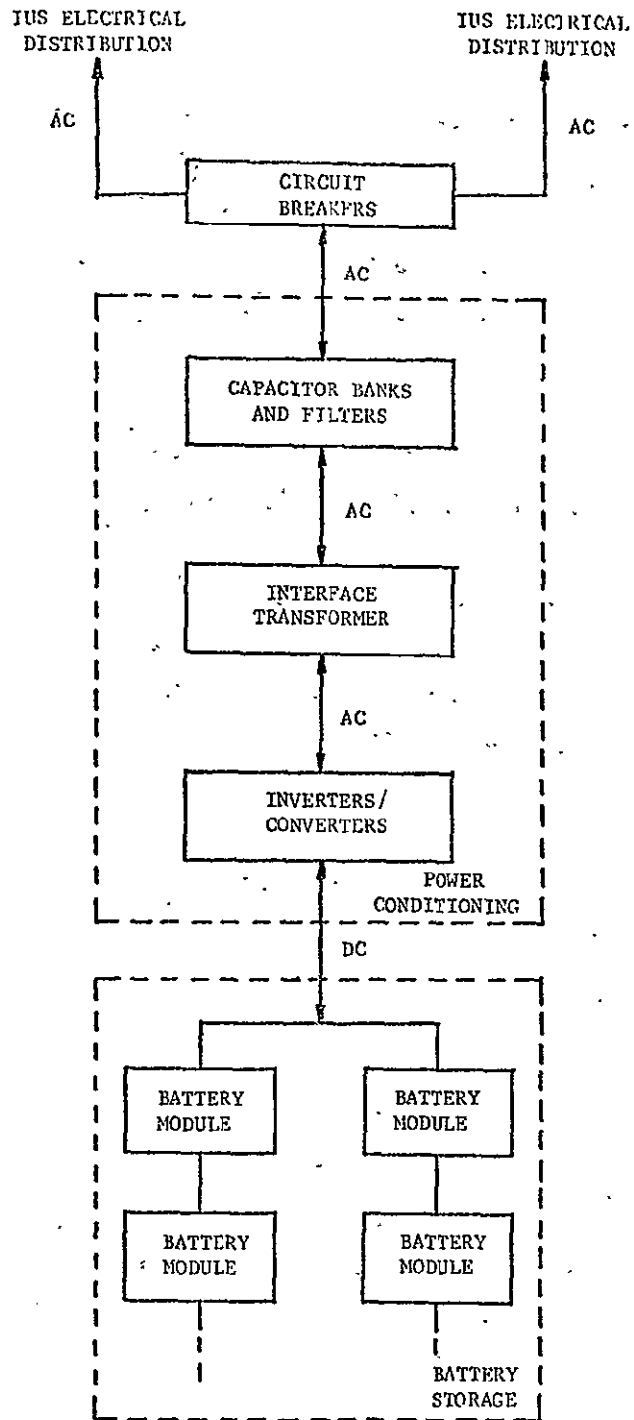


FIGURE 5.1. SCHEMATIC OF AN ELECTROCHEMICAL ENERGY STORAGE SYSTEM

- During charging, AC from the IUS generators is rectified to DC by the converter; during discharge, the inverse function is performed by the inverter. Although dual function equipment is available, some economy can result by using separate assemblies if the power ratings are quite different as a result of different charge/discharge rates.
- The transformer required for matching IUS/battery voltages should have provision for tap changing to allow for no-load/full-load voltage variation. The transformer also reduces some of the system harmonics.
- Filters are used to attenuate harmonics not suppressed by the transformer.
- Capacitor banks will be required to supply reactive power for power factor correction, since the battery supplies only real power.
- Lastly, the incorporation of the E/S installation into the IUS will require appropriate switchgear/relaying, protective equipment, and transmission buswork.

With proper integration, overall electrical efficiency exceeding 90 percent and even approaching 95 percent (suggested upper limit) should be realized.

Storage batteries have two related features that make them attractive for bulk E/S applications such as the IUS: (1) modularity of construction, and (2) rapid response. The first allows capability of the E/S being sized for any capacity requirement. Also, modularity permits versatile electrical assembly (i.e., series, parallel, or combinations); and, voltage/current (therefore, delivered power) control can be readily accomplished. The second feature makes the battery suitable for load following peak-shaving, intermediate load-leveling, and emergency power generation.

Alternative Approaches for Implementation

Alternative concepts for electrochemical E/S are derived basically from choices of active materials for the battery. The materials choice may then lead to one or more geometric configurations for practical implementation. At the present time, many types of secondary (i.e., rechargeable) batteries are in various stages of development. Each presents certain advantages/disadvantages for a given application such as the IUS.

In general, desirable features would include (1) adequate technical characteristics and (2) low life cycle costs. For the IUS, a third desirable feature would be near term (i.e., 1985) availability. Desirable technical characteristics include high energy density, acceptable power density, high energy efficiency, and long cycle life. Desirable cost characteristics include low initial installed capital costs and/or operation and maintenance (O&M) costs. These characteristics are interrelated and depend on the intended duty cycle. Clearly the challenge lies in providing desired technical characteristics at an acceptable cost; the implied tradeoffs are well illustrated for a water battery concept in Reference 1.

Because of the large number of electrolyte/electrode combinations being studied, qualitative arguments have been utilized to reduce the possibilities to a tractable number of preliminary candidates. Concepts that have been excluded in this manner are:

- o Organic electrolyte batteries--ruled out because of (1) high resistivity, which limits achievable power density, and (2) possible cycle life limitation owing to questionable stability of some organics.
- o Primary battery derivatives incorporating depolarizers (e.g., manganese dioxide)--rejected because (1) long cycle life not yet established, and (2) lack of evidence supporting scaling to MWh ratings within a reasonable time frame.
- o Batteries already superseded by improved or alternate concepts (e.g., lithium-chlorine and aluminum-chlorine)--many have been considered unsuitable for bulk E/S applications; others are being developed for specialized applications such as electric vehicles.

The resulting list of candidate concepts for preliminary screening is shown in Table 5.1. This list has been organized according to internal operating temperature levels.

Evaluation of Selected Candidate Concepts

Candidate Selection. Averaged performance and cost data have been collected from the literature for the preliminary list of battery candidates given in Table 5.1. These data are assembled in Table 5.2.

Actual cell cost data have been selected where possible. Thus, the costs for the well established nickel-cadmium, silver-cadmium, and silver-zinc batteries are considered realistic and appear to have limited chance for significant reductions. However, the costs for state-of-the-art nickel-hydrogen, silver-hydrogen, zinc-chlorine hydrate, lithium-metal sulfide, and sodium-sulfur candidates have a good chance of reduction below the \$50/kWh level.

A method has been devised for deriving a figure of merit, which, although arbitrary is useful in ranking candidates. This method utilizes both performance and cost parameters as shown in Table 5.3. The application of the method, along with results, is summarized in Table 5.4.

Of the 24 battery candidates listed in Table 5.4, 15 have a figure of merit exceeding 20 (the average possible score). This result indicates a possible relative superiority for these candidates in an IUS application.

Of the remaining 15 candidates several can be rejected by invoking the following arguments.

- Nickel-hydrogen--is rejected because of the high cost to achieve long cycle life. Additionally, alternatives to high pressure gas storage have yet to be demonstrated.
- Zinc-chlorine--is rejected in favor of the zinc-chlorine hydrate concept owing to the more hazardous storage of free chlorine instead of the combined form.

TABLE 5.1. PRELIMINARY LIST OF CANDIDATE BATTERY CONCEPTS
FOR IUS APPLICATION

Operating Temperature Range, deg K	Battery Designation ^(a)
Low (213-373)	PbO ₂ /Pb NiOOH/Cd NiOOH/Fe NiOOH/Zn NiOOH/H ₂ AgO/Cd AgO/Zn AgO/Pb AgO/H ₂ Zn/Cl ₂ Zn/Cl ₂ ·6H ₂ O Zn/Br ₂ Zn/O ₂ Fe/O ₂ Cd/O ₂ Redox (e.g., Cr ²⁺ , Cr ³⁺ /Cr ⁶⁺ , Cr ³⁺)
Intermediate (373-573)	Na/(Me)Cl ₂ ^(b) Na/O ₂
High (573-973)	Li-Al/Cl ₂ Na/S Li/S Li/Se Li/Te Li-Al/(Me)S

(a) The battery designation is given in terms of the major active materials.

(b) (Me) designates a metal.

TABLE 5.2. TYPICAL BATTERY PERFORMANCE AND LIFE DATA
REPORTED IN THE LITERATURE

Battery System ^(a)	Open Circuit Voltage, V	Average Operating Voltage, V	Maximum Reported Ah Capacity	Maximum Reported Power Level, kW	Operating Temperature Range, K	Typical Cycle Life, Cycles	Depth of Discharge, %	Reported Ah Efficiency, %	Reported Wh Efficiency, %	Energy Density, Whr/lb Wh/in. ³		Power Density, W/kg	Discharge Rate, hr	Estimated Cost \$/kg \$/kW \$/kWh		
<u>Low Temperature Operating Range</u>																
PbO ₂ /Pb	2.09	≥1.70	5,000	2.5	273-373	≤2,000	50	83-91	68-75	15	1.0	66	1-10	2.20	≥340	≥75
NiOOH/Cd	1.29	≥1.10	1,245	1.0	273-373	≤5,000	50	70-85	60-75	16	1.1	77	1-5	11.00	1500	360
NiOOH/Fe	1.37	1.20	750	—	273-373	≤3,000	80	80	60	26	1.0	99	1-3	4.62	—	≥65
NiOOH/Zn	1.71	≥1.30	140	—	273-373	1,200	90	-85	-70	25	1.5	154	1-5	≥4.40	—	≥85
NiOOH/H ₂	1.36	1.25	55	—	273-373	≤8,000	≥50	-95	—	30	≥0.8	165	2-15	—	—	1500
AgO/Cd	1.40	1.10	—	—	273-373	2,500	45	90-95	70	24	2.1	—	3	—	—	415
AgO/Zn	1.60	1.50	300	1.0	273-373	300	45	90-95	70-75	17	2.4	—	—	—	—	—
Ag ₂ O/Pb	—	0.90	—	—	273-373	20	—	—	—	45	2.7	143	1-15	55.00	—	≥440
Ag ₂ O/H ₂	1.40	1.10	500	—	273-373	1,000	"Deep"	—	—	50	0.8	—	—	—	—	840
Zn/Cl ₂	1.80	—	—	20.0	273-373	≥150	50	-95	-80	62	3.6	123	1	≥2.20	—	≥15
Zn/Cl ₂ (H ₂ O)	2.12	≥1.93	30,000	12.5	273-373	(b)	(b)	—	—	50	2.9	31	2-4	—	—	200
Zn/Br ₂	1.80	—	—	—	273-373	poor	—	—	—	21	—	59	—	—	—	—
Zn/O ₂	1.65	1.30	25	27.0	273-373	200	50	-70	—	59	2.3	59	1-10	≤7.26	100	≤36
Fe/O ₂	1.28	—	—	—	273-373	—	—	—	—	43	—	≤66	—	—	—	≤40
Cd/O ₂	1.22	≤0.85	12	—	273-373	≤500	"Deep"	—	—	39	3.5	—	2-10	—	—	—
Redox	0.74-1.74	—	0.38	—	273-373	(b)	(b)	—	—	—	—	13	5-8	—	≥185	≥35
<u>Intermediate Temperature Operating Range</u>																
Na/(H ₂)Cl	(≤4.00)	≈3.00	5	(1.0)	423-513	72	"Deep"	—	87	45	2.7	34	10	—	—	—
Na/O ₂	2.60	—	—	0.015	373-523	—	—	—	—	180	—	88	—	3.85	—	—
<u>High Temperature Operating Range</u>																
Li(Al)/(H ₂)Cl ₂	3.46	—	30	—	673-953	200	≥50	—	—	≥25	≥1.0	≤440	—	13.20	—	—
Li-Al/MeS	≤1.77	≤1.50	150	≤0.118	573-673	≥250	≤100	80	≤74	67	≤8.0	≤110	3-10	—	—	≥2130
Li/S	2.25	—	—	30	573-723	≥100	—	80-100	80-85	≤120	—	≤264	—	6.12	—	30
Li/Se	2.10	—	—	—	623-673	≥100	—	—	—	≤136	—	—	—	—	—	—
Li/Te	≥1.75	≥1.55	—	≤170	693-743	≥200	—	—	—	≤102	6.0	≤308	—	—	—	—
Na/Fe	2.08	1.84	700	—	558-673	≥200	50	≤100	≤90	71	≥5.5	≤117	1-8	≥2.20	133	≥1683

(a) Alloying additions or other principal components are sometimes used. These are given in parentheses. Me represents a metal.
(b) Indefinite cycle life with proper maintenance of solution compositions.

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TABLE 5.3. RATING CRITERIA FOR ESTABLISHING
FIGURE OF MERIT

Parameter and Value (a)	Assigned Score	
	1	2
Average operating voltage, V	< 1	≥ 1
Maximum Ah capacity reported, Ah	< 100	≥ 100
Operating temperature, K	> 373	≤ 373
Cycle life, cycles	< 1000	≥ 1000
Depth of discharge, percent	< 50	≥ 50
Wh efficiency, percent	< 75	≥ 75
Energy density, Wh/kg	< 55	≥ 55
Power density, W/kg	< 55	≥ 55
Projected near-term cost, \$/kWh (b)	> 50	≤ 50

(a) Discriminant numerical values are considered minimal for energy storage applications.

(b) Near-term refers to 1975 - 1985 time frame.

TABLE 5.4. DETERMINATION OF FIGURE OF MERIT FOR BATTERIES BASED ON LITERATURE DATA

Battery Type(a)	Average Operating Voltage	Maximum Ah Capacity	Operating Temperature	Cycle Life	Depth of Discharge	Wh Efficiency	Energy Density	Power Density	Subtotal(b)	Projected Cost	Figure of Merit(c)
PbO ₂ /Pb	2	2	2	2	1	1	1	2	13	(2) ^(d)	(26)
NiOOH/Cd	2	2	2	2	1	1	1	2	13	1	13
NiOOH/Pb	2	2	2	2	2	1	1	2	14	(1)	(14)
NiOOH/Zn	2	2	2	2	2	1	2	2	15	1	15
NiOOH/H ₂	2	1	2	2	2	(2)	2	2	(15)	(2) ^(d)	(30)
AgO/Cd	2	1	2	2	1	1	1	(2)	(12)	1	(12)
AgO/Zn	2	2	2	1	1	1	2	2	13	1	13
Ag ₂ O/Pb	1	1	2	1	1	(1)	1	(1)	(9)	(1)	(9)
Ag ₂ O/H ₂	2	2	2	2	2	(1)	2	(2)	(15)	1	(15)
Zn/Cl ₂	2	2	2	1	2	2	2	2	15	(2)	(30)
Zn/Cl ₂ 6H ₂ O	2	2	2	2	2	(2)	2	1	(15)	(2) ^(d)	(30)
Zn/Br ₂	(2)	1	2	1	(2)	(1)	1	2	(12)	(1)	(12)
Zn/O ₂	2	1	2	1	2	1	2	2	13	(2)	(26)
Fe/O ₂	(2)	1	2	1	1	1	2	(2)	(12)	(2)	(24)
Cd/O ₂	1	1	2	1	2	1	2	(2)	(12)	(2)	(24)
Redox	(1)	1	2	2	2	1	(1)	(1)	(11)	(2)	(22)
Na/(Me)Cl ₂	2	1	1	1	2	2	2	2	13	(2)	(26)
Na/O ₂	(2)	1	1	1	1	1	(2)	(2)	(11)	(2)	(22)
Li(Al)/(Me)Cl ₂	2	1	1	1	2	(1)	(2)	2	(12)	(1)	(12)
Li-Al/MeS	2	2	1	(1)	2	(1)	2	2	(13)	(2) ^(d)	(26)
Li/S	(2)	1	1	1	(2)	2	2	2	(13)	(2)	(26)
Li/Se	(2)	1	1	1	(2)	(1)	2	(2)	(12)	(2)	(24)
Li/Te	2	1	1	1	(2)	(1)	2	2	(12)	(2)	(24)
Na/S	2	2	1	1	2	2	2	2	14	(2) ^(d)	(28)

(a) Alloying additions for these principal components are sometimes used. These are given in parentheses. Me represents a metal.

(b) Parentheses indicate uncertainty in some of the data (see text). These figures may be revised as new data become available.

(c) Subtotal x Projected Cost.

(d) There is some evidence that with a sufficient R&D effort costs could fall below \$50/kWh.

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- Zinc-air--is rejected for lack of a low cost, long life oxygen electrode. A potential problem of internal shorting, with resultant loss of capacity, could arise as a result of zinc migration during cycling.
- Iron-air, sodium-air, and cadmium-air--all are rejected, again because of a lack of a suitable oxygen electrode.
- Lithium-sulfur, lithium-selenium, and lithium-tellurium--all are rejected because they are superseded by lithium-alloy-metal sulfide concepts.
- Sodium-metal chloride--is rejected in favor of the lithium-metal sulfide concept, which is at a more advanced stage of development
- Redox--is also rejected as being in too early a stage of development to be a near-term contender for IUS service.

Four candidates, each of a distinctly different nature from the others, remain for detailed consideration in an IUS setting. These four are listed below together with an anticipated time schedule for demonstration in The Battery Energy Storage Test Facility (BEST) at a (power, energy) level of (1-2 MW, 1-10 MWh) (2)*.

Lead acid (PbO_2/Pb)	1978-1979
Zinc-chlorine hydrate ($\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$)	1979-1980
Lithium-metal sulfide (Li/MeS)	1980-1982
Sodium-sulfur (Na/S)	1981-1982

These four concepts are being suggested by their developers as near-term contenders for bulk E/S applications. The first two represent concepts designed to operate at relatively low internal temperatures. Although operating as a static system, in state-of-the-art technology, the lead-acid battery could operate with a flowing electrolyte (to improve heat transfer) in an advanced design. The zinc-chlorine hydrate concept does employ a recirculating electrolyte that also transports active materials. The last two concepts on the list will operate at relative high temperatures (see Table 5.1) and also feature permanent encapsulation of the active materials within individual cells.

* The BEST Facility is an industry development being coordinated by the Electric Power Research Institute (EPRI).

Technical Characteristics. Having selected four concepts as candidates for near-term IUS application, attention is focused upon their technical characteristics. Each concept is treated separately and its discussion begins with a brief background description. It must be emphasized that the characteristics described are based upon published information, and BCL's interpretation of these published data. As new information becomes available this should be incorporated in these analyses.

Lead-Acid Battery. Because the lead-acid battery has been in use for over 100 years, its unusual nomenclature has persisted. In contemporary practice, a battery is identified in terms of the major constituents of its electrodes; hence, the correct and preferred description is lead dioxide-lead battery.

From an application standpoint there are four basic kinds of lead dioxide-lead batteries available: (1) Units for automotive vehicle starting, lighting, and ignition (SLI); (2) traction batteries for industrial and recreational vehicle (e.g., fork-lifts and golf-carts); (3) stationary units for public buildings and critical installations (standby/emergency); and (4) bulk energy storage units, such as aboard submersible craft. Although storage capacity required for IUS peak shaving/load leveling is much larger, the application clearly falls in the last category.

The manufacturing technology for conventional PbO_2/Pb batteries is well established, and the manufacturing cost relatively well known. Data for PbO_2/Pb batteries are taken as a reference for other battery storage systems. Although the performance/cost of state-of-the-art PbO_2/Pb batteries leaves much to be desired, the lead time for this installation is considered to be short. For example, it has been suggested⁽²⁾ that submarine batteries be used for initial tests of the BEST Facility that are scheduled for about 1978-79. Although these batteries would not be optimized for an energy storage application, two important related benefits would result. First, the suitability of the facility for testing large storage batteries would be evaluated. Second, operating data would be accumulated for a large battery system, an experience that could help to resolve some presently unanswered questions, such as reliability.

Conventional PbO_2/Pb battery cells consist of one or more positive electrodes, containing a specially formulated lead dioxide, and one or more negative electrodes, which contain essentially metallic lead. These active materials are supported on lead-alloy current collectors (grids). All the positives in a cell are joined to a lead-alloy terminal post, while all the negatives are joined to another post. Different polarity results when the sulfuric acid electrolyte is added. A separator is used between positive/negative electrode pairs to prevent an electronic conduction path (short-circuit) between the two, and to achieve uniform, parallel spacing of the electrodes. Each (electrode pair and electrolyte) cell has a low-drain voltage of about two volts; hence, they are normally connected in series to form a battery of the desired voltage (usually 6 or 12 volts). The battery cases, which normally incorporate the cell partitions, traditionally have been made from hard rubber or glass; but in recent years synthetic rubbers and plastics (e.g., polypropylene) have become popular.

Over the last half century the performance of conventional lead dioxide-lead batteries has been improving slowly, but steadily. The duty cycles for energy storage applications resemble closely those for traction batteries having daily deep discharge/recharge cycles; hence, data for this type of battery are used here as a baseline. Projections have been made from these data to obtain performance estimates for near-term advanced batteries.

The energy efficiency of a battery storage device is important in determining the amount of energy that has to be stored in order to deliver the required electrical output to the load. The energy efficiency will be some function of battery type, design and method of construction, duty cycle, and power conditioning equipment. In any battery system, inefficiencies during charging and discharging are manifested by voltage losses and resultant heating effects. These losses increase with increased current density at which individual cells operate. However, it would be impractical to operate at too low a current density, because the size of the storage device would be larger and (usually) more expensive. Thus, a compromise in operating current density must be sought. As shown in Table 5.2 over the range of current densities typical of present applications, the energy efficiency is in the range of 68 to 75 percent,

for 50 percent depth of discharges. Ideally, for load-leveling energy storage applications, the depth of discharge should be as close as possible to 100 percent in order to keep the capital costs for storage as low as possible. At the present time this is not practical for conventional PbO_2/Pb batteries; perhaps a 75 to 80 percent depth of discharge would be more realistic. The net effect of this using a 75 to 80 percent depth of discharge would be to increase the number of allowable discharge cycles while slightly penalizing the energy efficiency. Considering that the round-trip electrical efficiency of the power conditioning subsystem is expected to be in the range of 90 to 95 percent, an overall energy efficiency of 65 percent has been selected as being realistic for this battery candidate in an IUS application.

The 61 kWh/m^3 (1.73 kWh/ft^3) energy density shown in Table 5.2 is typical of conventional traction and stationary batteries. Modern PbO_2/Pb batteries being manufactured specifically for electric vehicle applications are exhibiting energy densities of about 92 kWh/m^3 (2.6 kWh/ft^3). However, these figures do not take into account the extra volume required for access, cooling, ventilation, safety control, and performance monitoring required in large battery installations, such as would be needed for the IUS application.

A recent study⁽³⁾ of a peaking type PbO_2/Pb battery for use as an electric utility distribution system gives data which is equivalent to a value of 44 kWh/m^3 (1.25 kWh/ft^3) for the battery alone, or 35 kWh/m^3 (1.20 kWh/ft^3) for the battery storage subsystem. These latter values do take into consideration the volume required for access, cooling and ventilating ducts, etc., and hence are more realistic than those given in Table 5.2 for much smaller systems.

Studies performed for EPRI to arrive at a conceptual design for the BEST Facility⁽⁴⁾ considered submarine PbO_2/Pb batteries for storage subsystems up to 10,000 kWh (1 MW, 10 hr discharge). The conclusion reported in that study was that for the most compact arrangement the cells should be free-standing (i.e., case material rigidly supports the weight of the electrodes and electrolyte), and water-cooled. The largest capacity cells available should be used to minimize the floor space occupied. Most large capacity cells available are air-cooled (conversion to water cooling is not generally possible). However,

even if water-cooled, space must still be allowed for a ventilation system to discharge the gases (especially hydrogen) generated during cycling. If the facility ceiling height is restricted, at least five feet should be left between rows of cells connected in series to enable access by a forklift truck to remove and replace faulty cells. Without a ceiling height restriction, an overhead crane can be used for maintenance and the floor space needed for a given battery capacity could be reduced. The effect on volume requirements would then depend upon the size of the particular cells selected and could have to be estimated for each installation. Using Exide MAZ-31A cells as an example, the data given in Reference 4 would suggest energy densities in the range 3.53 to 5.30 kWh/m³ (0.10-0.15 kWh/ft³) depending on the type of cooling duct and maintenance equipment employed.

From the preceding discussion, if conventional state of the art PbO₂/Pb batteries are used in an E/S facility, the installed energy density could not be less than about 3.53 kWh/m³ (0.10 kWh/ft³) but would not exceed 35.3 kWh/m³ (1.00 kWh/ft³). Because the latter estimate was based upon a study which assumed certain improvements in present day performance, the low value is often preferred. However, because there is a strong indication that the latest batteries being developed for electric vehicle applications have energy densities some 50 percent higher than that shown in Table 5.2, the energy density value chosen for the IUS application is 5.30 kWh/m³ (0.15 kWh/ft³).

If the power conditioning subsystem cannot be housed in an existing structure within the IUS, then the overall installed energy density could be reduced by up to 50 percent. Hence the energy density of the storage system, if built today, would likely be in the previously suggested range of 3.53 to 5.30 kWh/m³ (0.10-0.15 kWh/ft³). As an example of the size of building required for one set of operating parameters of the IUS, consider the 1000-Unit Apartment case, with 5 baseload generators installed, and a required storage capacity of 1310 kWh for an electrochemical storage device with a round trip efficiency of 65 percent (i.e., 1,056 kWh could be discharged to the load over a 4 hour period). With an energy density of 3.53 kWh/m³ (0.10 kWh/ft³) the building volume requirement could be 371 m³ (1,310 x 10 = 13,100 ft³). If the ceiling height is assumed to be about 4.57 (25 ft), then the floor area is about 84 m² (900 ft²), and a typical floor plan might be (30 x 30 or 40 x 22.5 ft).

In order to minimize the life cycle cost of an electrochemical E/S system it is important that the service life be as long as possible. Present stationary PbO_2/Pb batteries for emergency standby power have a life of about 20 years, but these are infrequently discharged. In contrast, automobile (SLI) batteries have a life of between 2 and 5 years, depending on the quality sought by the manufacturers. Traction batteries, operating at depths of discharge of 50 to 80 percent, give lives of 5 to 7 years (1000 to 2000 cycles, as shown in Table 5.2). When a large number of cells are connected in series to form a battery, and when a large number of these batteries are connected in series and/or parallel to form a storage system, additional problems arise that shorten life. For example, thermal runaway, which can occur with cells or batteries connected in parallel, can lead to premature failure. Mismatch of cell capacities, which can occur for large numbers of cells connected in series, can lead to cell reversals and again to premature failures. For large battery systems, with hundreds of cells electrically connected together, it may be economically impractical* to control the voltages during charge and discharge very closely, so that cell mismatch is likely. For the above reasons, and because operating experience has not been obtained with systems of MWh storage capacity, a realistic life for state of the art battery systems is expected to be 5 years (1000 to 1250 cycles). Then for a desired 20 year energy storage system life, the batteries would have to be replaced three times.

Thus far, only state-of-the-art PbO_2/Pb batteries have been considered. However, considerable effort is being expended by several companies to design improved batteries for E/S application. Two approaches are apparently being taken: (1) modification of existing designs and technology; and (2) redesign based on system requirements. Emphasis appears to be placed upon the former. Taking note of recent trends in performance of PbO_2/Pb batteries, it is possible to anticipate improvements that might be expected over the next decade.

- The energy efficiency of the battery should approach 75 percent, which, coupled with a power conditioning subsystem efficiency in the range of 90 to 95 percent, means that an overall system efficiency of 70 percent should be obtained.

* One recourse would be to supply an "equalizing" charge at the close of each week, when electrical demand is low.

TABLE 5.5. SUMMARY OF TECHNICAL CHARACTERISTICS OF CANDIDATE BATTERY CONCEPTS FOR IUS APPLICATION

Battery Concept	Round Trip Efficiency, Percent ^(a)				Energy Density, kWh/m ³				Life, yr ^(b)	
	Battery Subsystem		Total System		Battery Subsystem		Total System		Battery Subsystem	
	High	Low	High	Low	High	Low	High	Low	High	Low
PbO ₂ /Pb	75	70	70	65	0.23	0.15	0.15	0.10	7	5
Zn/Cl ₂ ·6H ₂ O	80	70	75	65	0.45	0.33	0.28	0.23	10	5
Li/MeS	82	72	76	67	0.37	0.33	0.25	0.23	5	2
Na/S	80	70	75	65	0.25	0.17	0.19	0.14	5	2

(a) Battery subsystem includes any necessary heating, cooling, safety equipment, etc. (see text). Total system includes volume requirements for the power conditioning subsystem estimated from efficiency. "High" designates an optimistic value that may be achieved by 1985; "low", a realistic value achievable today.

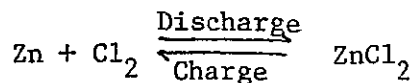
(b) Life extends until performance is unsatisfactory for the application. Life of power conditioning equipment should be 20 years or more.

- As mentioned earlier, there has been about a 50 percent increase in the energy density for electric vehicle batteries over recent years. If the same amount of improvement is assumed for energy storage batteries, then the equivalent energy density for the overall E/S system would be between 5.30 and 7.95 kWh/m³ (0.15-0.23 kWh/ft³). The former value is given in Table 5.5 as a near-term goal.
- A goal for many battery manufacturers is a 7 year life, such that the batteries would only have to be replaced twice during a 20 year period (as opposed to the previously mentioned three times for state-of-the-art batteries). To obtain a life in excess of 10 years for PbO₂/Pb batteries, refurbishment or replacement of electrode(s) and electrolyte would probably be necessary for the type of duty cycle required of bulk energy storage.

Zinc-Chlorine Hydrate Battery. Zinc-chlorine batteries which have been in existence for some time, and have been proposed for some vehicular applications. There was some concern⁽⁵⁾ about the possible hazard posed by release of gaseous chlorine in the event of battery container damage during a crash of the vehicle. The Udyllite Company Energy Development Laboratory* overcame this potential problem by hydrating the chlorine. This compound is a safe, easily handled solid at ambient temperatures. During cell operation it is allowed to decompose and release chlorine gas at the electrode surfaces to participate in the cell reactions. The drawback with the use of the chlorine hydrate is that there must be an external, refrigerated store and a means of circulating the hydrate between the cell stack and the store. This increases the complexity of the system and, in turn, somewhat decreases the effective system energy density. EDA is actively pursuing this concept for energy storage applications, and plans have been made⁽⁶⁾ to include this battery concept for testing in the BEST Facility.

* Now associated with Energy Development Associates (EDA).

The overall cell reaction is:



The theoretical cell voltage for this reaction is 2.12 volts, (comparable to PbO_2/Pb). During discharge, zinc is oxidized at the negative electrode, and chlorine hydrate is reduced at the positive electrode. Since the oxidized zinc is soluble in the zinc chloride electrolyte, a clean zinc surface is always present while the active material remains. This contrasts to zinc electrodes in alkaline electrolytes that become covered with a zinc hydroxide film. During recharging, the zinc chloride formed on discharge reverts to zinc and chlorine gas which is dissolved in the circulating electrolyte.

Very little data have been published about the construction and the performance of zinc-chlorine hydrate batteries. Apparently, early versions used graphite substrate for both electrodes, (i.e., zinc being deposited on the graphite to form the negative electrode, and porous graphite being used for the positive). There is reason to believe that the larger batteries for energy storage applications would use noble metal-catalyzed titanium electrodes instead of graphite (i.e., zinc being deposited on titanium foil to form the negative, and porous titanium sheets being used for the positive). Although relatively expensive, titanium is easier to fabricate and join than graphite, is lighter, and yields smaller polarization losses at a given current density.

A distinctive feature of the zinc-chlorine hydrate battery is that damage does not result from overcharging/overdischarging. The latter refers to continued discharge after all the zinc has been removed from the negatives which causes the electrodes to reverse polarity and evolve chlorine. However, this chlorine is reduced at the positive electrodes, and the net result is just a transfer of chlorine between electrodes. During overcharging all of the zinc chloride in the electrolyte would be converted to zinc metal and chlorine gas. Upon further charging the electrodes would become appreciably polarized, and the cell reaction would change to water electrolysis to yield hydrogen and oxygen. However, no damage to the battery could result.

For load-leveling applications, it has been recommended⁽⁶⁾ that the zinc electrodes be completely discharged, so that upon recharging a uniform deposit is obtained. A common problem with zinc electrodes is "shape change", i.e., a redistribution of the active materials with cycling. Such a shape change, and/or the deposition of dendritic zinc can cause cell shorting. Therefore, careful attention must be paid to cell design and operating parameters, and an electrolyte additive may be needed to suppress dendritic zinc growths during recharging. The recommended operating parameters are a four hour charge/four hour discharge duty cycle, with the battery operating at constant voltage (i.e., approximating constant power). Time-series and time-parallel switching of battery modules⁽⁶⁾ could enable any load profile to be accommodated.

The largest stationary system reported to date⁽⁹⁾ is a 12.5 kW battery. Earlier a 3 kW battery had been installed in a Chevrolet Vega automobile to demonstrate its feasibility for an electric car.⁽⁷⁾ Gould, Inc., in conjunction with the battery developer, EDA, and with the support of EPRI⁽⁶⁾ are focusing on stationary applications, with a goal of testing a 1 kWh (0.1 kW, 10 hr) cell for load leveling in the near future.

Table 5.2 contains a summary of published technical information about the zinc-chlorine hydrate battery. These data do not include values for ampere-hour or watt-hour efficiencies; however, data supplied by the developers for the type of preferred duty cycle described above indicate that the energy efficiency could be as high as 77 percent for small batteries. If the duty cycle is changed to 8 hours charging/4 hours discharging a slight improvement in energy efficiency would be realized, and a value of 81 percent might be possible, again based on a current density of 50 mA/cm^2 ($\sim 50 \text{ A/ft}^2$) for the four hour rate. Thus in Table 5.5 a value of 80 percent has been selected as the optimistic value for the battery subsystem exhibiting some improvement in performance. For a large capacity system, and with an electrical efficiency of 92 percent for the auxiliary equipment such as pumps and heat exchanger, a more realistic value for near-term applications might be 70 percent. Assuming the efficiency of the power conditioning subsystem to be in the range of 90 to 95 percent, as used previously, the total system round-trip efficiency would then lie in the range of about 65 to 75 percent, as indicated in Table 5.5.

The battery developers⁽⁹⁾ have estimated the energy density of a 12.5 kW, 50 kWh battery for stationary applications to be about 175 kWh/m^3 (50 kWh/ft^3). However, when scaled up into battery subsystems suitable for the IUS application, without design optimization, the energy density could be as low as 17.5 kWh/m^3 (0.5 kWh/ft^3). With the larger battery subsystems it is anticipated that there would not be a separate electrolyte store, chlorine hydrate store and sump, and other auxiliary equipment for each battery module. Instead one centralized facility would serve the entire battery array; hence the overall energy density rating should be improved. However, data presented in Reference 4 indicate that for a 10 MWh (1 MW) battery floor area roughly between 186 and 260 m^2 (2000 – 2800 ft^2) could be required. Assuming a ceiling height of 4.6 m (15 ft) the energy density will fall in the range of 8.5 to 11.7 kWh/m^3 (0.24 – 0.33 kWh/ft^3). Some of the auxiliary equipment could be situated outside the structure for the battery cell stacks, and the control and safety equipment. This would reduce the volume requirements for the structure, but probably would not affect the floor area required. Thus an improvement in energy density would be expected to result possibly in values in the range of 11.7 to 15.9 kWh/m^3 (0.33 – 0.45 kWh/ft^3). In Table 5.5, therefore, a high value for the energy density would probably be in the range of 15.9 and 17.7 kWh/m^3 (0.45 – 0.50 kWh/ft^3) and the former value has been selected as a goal for attainment by 1985. A battery subsystem built now would probably have an energy density in the range of 8.5 – 11.7 kWh/m^3 (0.24 – 0.33 kWh/ft^3) and the latter value has been selected for this study.

The energy density of the total storage system will be lower than the above values because of the volume requirements of the power conditioning subsystem. This volume requirement is assumed to be the same for all the battery types considered in this characterization, because the electrical specifications are similar for a given IUS application. It is assumed that the power conditioning subsystem volume requirement is 396 m^3 ($14,000 \text{ ft}^3$) therefore, the total system energy density should fall in the range of 8.0 to 9.9 kWh/m^3 (0.23 – 0.27 kWh/ft^3) as shown in Table 5.5.

Results of cycling tests with large battery assemblies have not been published. Reported goals for the zinc-chlorine hydrate battery include cycle life of 2500 cycles (equivalent to 250 cycles per year for 10 years). Thus, 10 years has been given as the optimistic value for life in Table 5.5. Because this is a battery type which operates at ambient temperature and the cell reactions do not involve solid state phase changes, the prognosis for achieving a relatively long cycle life is good, provided catalyst activity and electrolyte solution purity is maintained. For the near term, a life of 5 years has been assigned to this system as was done for PbO_2/Pb concept.

Lithium-Metal Sulfide Battery. There are many variations of the lithium-chalcogen battery some of which have been indicated in Table 5.2. Of these types, the batteries being developed for stationary E/S applications have lithium alloy negative electrodes; metal sulfide positive electrodes, and lithium chloride-potassium chloride eutectic electrolyte. Because these types of cells operate at about 673 K (750 F), ceramics such as boron nitride, aluminum nitride, beryllium oxide, or aluminum oxide are necessary as cell separators. Lithium-metal sulfide batteries are being developed primarily by Argonne National Laboratory (ANL) and Atomics International (AI). The ANL cell design incorporates a lithium-aluminum alloy anode and a ferrous or ferric sulfide cathode, with or without the addition of other metal sulfides. Flexible boron nitride cloth (sometimes in conjunction with zirconia) is used as a separator⁽⁶⁾ in the laboratory demonstration cells. The AI cell design currently incorporates a lithium-silicon alloy anode, and a mixed ferrous/ferric sulfide cathode. According to Reference 6 the separator is rigid and comprises BeO and Al_2O_3 , while the cathode current collector is carbon felt.

Most development work has centered around the use of iron sulfides as the cathode active material because of their availability and relatively low cost. Simplified cell reactions can be written as follows:

<u>Reaction</u>	<u>E_L - Volts</u>
$2\text{Li} + \text{S} \rightarrow \text{Li}_2\text{S}$	2.17
$2\text{Li} + \text{FeS}_2 \rightarrow \text{Li}_2\text{S} + \text{FeS}$	1.95
$2\text{Li} + \text{FeS} \rightarrow \text{Li}_2\text{S} + \text{Fe}$	1.64

where E_L is the cell voltage measured against a lithium reference electrode. The three reactions show that as the sulfur is "diluted" with iron the cell voltage diminishes. The 50 percent aluminum alloyed with the lithium in the ANL cell to reduce its corrosiveness does not contribute to the cell reactions, but does lower the cell voltage by about 300 mV; however, for simplicity these effects have been neglected. The use of a metal sulfide in place of sulfur alleviates corrosion problems. Although this approach has a detrimental effect on efficiency, energy density, and power density, and hence cost, the longer cell life is a desirable gain in the tradeoff. The energy efficiency and utilization factor for both (FeS_2 and FeS) sulfide cathodes are similar; however, FeS_2 yields a higher cell voltage during the initial portion of discharge and has a 20-25 percent higher specific energy than FeS as a cathode material. The more reactive FeS_2 does require use of an inert current collector material such as molybdenum, tungsten or carbon felt, which is expensive. With electrodes containing FeS , an inexpensive material such as iron can be used as the current collector. The lower cost, and greater availability/fabricability of iron for current collectors has caused emphasis to be shifted towards the use of FeS as a cathode for energy storage batteries⁽¹⁰⁾. However, there is a problem with excessive volume expansion when FeS electrodes are cycled⁽⁶⁾ that must be resolved before this type of electrode can be fully exploited.

The Li-Si alloy used as an anode by AI is a relatively new development that has recently been reported in the literature⁽¹¹⁾. Advantages over lithium or Li-Al alloy electrode materials are claimed to be a reduced rate of self-discharge and corrosion during cell operation. In terms of ampere hours per gram, the capacity of these electrodes is also greater, and the voltage loss due to alloying is significantly smaller. An 100 Wh prototype cell has been built by AI, incorporating the Li-Si anode material. This cell was cycled 80 times over a period of 2-5 months. The results were promising, and plans call for building a larger cell followed by eventually scaling up to about 1 kW (2-5 kWh).

The coulombic efficiency of Li/MeS batteries can approach 100 percent; thus, the watt hour efficiency can be high. Laboratory scale cells have been operating with energy efficiencies between 74 and 80 percent, according to data supplied by ANL⁽¹²⁾. Predictions have been made by ANL⁽¹³⁾ that a nominal 1 MW (10 MWh)

energy storage battery subsystem could achieve an efficiency of 80 percent for a five hour charge period, and 85 percent for a seven hour charge period, both on a daily duty cycle. For a similar 5 hour charge, 10 hour discharge duty cycle, and a similar cell construction, AI reports watt-hour efficiencies in the range of 70 to about 84 percent. Efficiency data have yet to be presented for cells incorporating Li-Si alloy anodes. Combining the ANL and AI data it is projected that near-term Li/MeS battery subsystems; operating at a current density below 100 A/cm^2 , will have an energy efficiency of about 72 percent. However, by 1985 efficiencies as high as 82 percent may be obtained. These estimates are incorporated in Table 5.5. As before, if the power conditioning subsystem efficiency is between 90 and 95 percent over this time frame, then total energy storage system efficiencies will be in the range of 67 to 76 percent.

In Table 5.2 the estimated energy density for small laboratory cells could be as high as 488 kWh/m^3 (13.8 kWh/ft^3). It is unreasonable to expect that in scaling up laboratory cells by many orders of magnitude into an energy storage battery such an energy density could be achieved. Preliminary design studies for (1 MW, 10 MWh) load leveling batteries made for the BEST Facility Project Team^(13,14) give calculated values of about 148 kWh/m^3 (4.2 kWh/ft^3) for ANL battery modules, and 198 kWh/m^3 (5.6 kWh/ft^3) for AI module designs. When these battery modules are incorporated into a battery storage subsystem, allowing space for access, controls, battery replacement, ventilation and safety equipment, the energy density is significantly reduced⁽⁶⁾. For the subsystem the energy density for both designs will fall in the range of 8.1 to 12.4 kWh/m^3 ($0.23\text{--}0.35 \text{ kWh/ft}^3$) depending on the ceiling height assumed. A smaller floor area is required by the ANL battery, but the ceiling height requirement is greater for the overhead removal of failed groups of cells which are stacked vertically in the referenced design.⁽¹⁴⁾

An estimate of the energy density of a battery subsystem suitable for IUS applications, based upon available data, is 11.8 kWh/m^3 (0.33 kWh/ft^3) the value given in Table 5.5.

Over the next decade subsystem design optimization and improvement in cell performance are expected. For example, use of a Li-Si alloy anode should result in a higher average cell operating voltage,⁽¹¹⁾ say 1.62 versus 1.50 volts for cells incorporating a Li-Al alloy anode, and operating at about 50 mA/cm² (46 A/ft²). Coulombic efficiency is expected to be maintained close to 100 percent; therefore, an increase in energy of about 8 percent can be assumed. The use of Li-Si alloy anode also is expected to increase the gravimetric coulombic density (Ah/kg) of a cell by about 25 percent⁽¹¹⁾, and hence the volumetric coulombic density (Ah/m³) of a cell by about 4 percent. Thus, by incorporating just these improvements it is projected that an energy density of 13.1 kWh/m³ (0.37 kWh/ft³) would be achieved in the near future.

For the total energy storage system, making allowances for the power conditioning subsystem, as described previously, the energy density will be about 8.1 kWh/m³ (0.23 kWh/ft³). With improvements in design and performance a value of 8.8 kWh/m³ (0.25 kWh/ft³) could be achieved. These estimates are also included in Table 55.

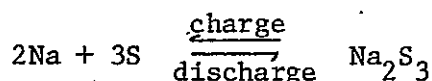
Cycle life data for energy storage batteries, or even groups of cells, need to be established for the lithium-metal sulfide concept. As mentioned earlier, the high temperature of operation, and the corrosive nature of the active electrode materials, do not favor long operating life. To date, over 80 cycles (2000 hours of operation) have been obtained with sealed lithium-metal sulfide experimental units^(11,12). Depending on the length of the discharge in the duty cycle (5 or 10 hours) it should be possible to attain a life between 1 and 2 years in the first generation of batteries. The design goal is about 1500 cycles or 5 to 6 years of continuous operation⁽¹²⁾. Thus the low value for the life in Table 5.5 is given as 2 years and the high value as 5 years. As operating experience is gained with batteries of this type, the above figures can be modified accordingly.

Sodium-Sulfur Battery. There are two variations of sodium-sulfur batteries. Both contain a molten sodium negative electrode and a molten sulfur positive electrode. However, the Ford, General Electric and TRW Cells have a solid

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beta-alumina electrolyte permeable to sodium ions, while the Dow cell uses hollow glass tubes as the solid electrolyte. The literature^(15,16) indicates that GE and TRW efforts are directed toward stationary batteries for energy storage applications. However, in Table 5.2 the data are averaged for all manufacturers. Specific technical data for the GE and TRW concepts will be given below.

The Na/S cell functions at elevated temperatures in the range of 558 to 673 K (285-400 F). The sodium-ion conducting solid electrolyte is used to allow the cell reactions to occur at a controlled rate, while at the same time preventing electronic shorting of the cell. Current collectors are presently made from graphite; but, less expensive materials (e.g., other forms of carbon) need to be developed.

The cell reaction is represented by:



During discharge the elemental sodium is ionized at the solid electrolyte interface, and the sodium ions migrate into the sulfur compartment. A reaction occurs on this side of the electrolyte to form polysulfide ions, which are subsequently discharged to complete the electron flow. The open circuit voltage of a charged cell is about 2.08 volts, while at 100 percent discharge the open circuit voltage is about 1.80 volts. The cell operating voltage is approximately proportional to the cell current, which is typical of cells operating over this temperature range.

Compared with many other battery systems, sodium-sulfur batteries do not suffer from secondary reactions which affect capacity retention and efficiency⁽¹⁹⁾. This is advantageous, because charged cells may be stored for extensive periods of time at elevated temperatures. However, along with other battery types which exhibit this characteristic, one consequence is that when cells are connected in series to form batteries, because the current is common to all cells, the cell with the smallest capacity will reach the end of discharge first. The internal resistance of this cell increases and the discharge

efficiency decreases as Na_2S_3 is formed, with the result that considerable internal heating occurs, and less power is delivered to the load. Permanent damage can result from the overheating. A similar phenomenon can also occur on charging; hence, it is extremely important that cells are matched as closely as possible (in terms of capacity and end of charge or discharge voltage) when assembling the batteries. A discussion of the effects of cell mismatch is given in Reference 16.

The two approaches to cell design are exemplified by the TRW and GE batteries. The TRW cell incorporates a flat ceramic plate (disc) beta-alumina electrolyte. Individual cells are completely contained, and stacked to form battery modules. The GE cell incorporates a tubular beta-alumina electrolyte, flanged at one end, and closed at the other. A small GE battery consists of many of these sodium-filled tubes immersed in a common vessel containing the sulfur, and graphite current collector.

There are advantages and disadvantages with the use of both forms of electrolyte geometry^(6,17,18). Tubular designs reduce the length of seal required, and remove the seal from the hot zone. Planar designs may be better suited for mass produced cells, and minimizing cell volume. However, the poor mechanical strength of the ceramic electrolyte and the longer seal requirement limits the size of the cell at the present time. In Reference 17 it was concluded that the planar cell design was best suited for low capacity, high rate applications; while the tubular cell design was best suited for high capacity, low rate applications. It remains to be seen on this basis whether the GE design is more suitable for load-leveling applications, and the TRW design for peaking applications.

Another materials problem to be resolved is the selection of the type of beta-alumina for use in the cells. Besides beta there exist beta prime (β') and beta double prime (β'') modifications.⁽⁶⁾ TRW is also using a MgO-doped β -alumina in its cell design. The final choice will depend on the fabrication procedure selected, the desired sintering temperature, the degree of sensitivity to water which can be tolerated, life, mechanical properties, and electrical properties desired. The GE cell is reported⁽⁶⁾ to be using a β -alumina electrolyte.

Table 5.2 shows that the highest reported watt-hour efficiency for laboratory scale cells is about 90 percent. Data reported by TRW and GE indicate that the high value may be 82 percent for these types of cells incorporating desirable materials and methods of construction. At the BEST Facility Workshop in 1975, manufacturers indicated that small (kW size) batteries built to date have shown energy efficiencies up to 79 percent. A realistic near-term goal is thus considered to be 80 percent at practical current densities, and for a daily duty cycle of 10 hours discharge, and 5 to 7 hours charge. During overcharge and overdischarge, as with other battery types, the energy efficiency decreases. Also, if the ceramic electrolyte ages, i.e., its resistivity increases with time, the round trip battery (energy) efficiency will decrease. The low value for the energy efficiency, will probably be similar to the other battery types discussed, namely about 70 percent.

The efficiency is also a function of the design power capability and the operating power level. For example, with the GE module design⁽¹⁵⁾, at the design efficiency of 82 percent no auxiliary power is needed to maintain cell temperatures within the desired range under prescribed operating conditions. However, if the battery operates at lower than its design capacity, the efficiency value observed is reduced because of the need for auxiliary heating to maintain cell temperature (heating due to resistive losses is inadequate). Thus, for the same duty cycle, at 50 percent of the design power output the efficiency would fall from 82 to 79 percent, and not increase to about 91 percent as expected if thermal effects are ignored. This relationship between electrical efficiency and thermal requirements must be taken into account for all battery systems operating at elevated temperatures.

With power conditioning subsystem efficiencies in the range of 90 to 95 percent, the total system round-trip efficiency is calculated to fall in the range of 65 to 75 percent, which is similar to the range for the zinc-chlorine hydrate and lithium-metal sulfide battery systems shown in Table 5.5.

Preliminary design data^(15,16) for battery modules which would comprise the storage part of the battery subsystem, indicate that the energy density for GE batteries would be about 88 kWh/m^3 (2.49 kWh/ft^3) for a 1 MW, 10 MWh system.

On the same basis TRW batteries would exhibit an energy density of about 87 kWh/m³ (2.46 kWh/ft³). These values may be compared with an average value of 335 kWh/m³ (9.5 kWh/ft³) which has been reported for small laboratory cells (Table 5.2).

When considering the whole battery subsystem an energy density of about 87.5 kWh/m³ (2.47 kWh/ft³) is not likely to be obtained for reasons explained earlier. Subsystem descriptions given in Reference 4 indicate that the TRW system will incorporate an extensive ducting and heat exchange system to keep the cells continuously under a blanket of nitrogen, which also serves as the heat transfer medium. On the other hand, plans for the GE subsystem indicate that natural convection will be utilized to cool the individual small batteries, and these will be spaced further apart than the TRW cell stacks. Assuming a ceiling height of 4.6 m (15 ft) the energy density of the GE battery subsystem is calculated to be about 6.00 kWh/m³ (0.17 kWh/ft³) while that of the TRW system is calculated to be about 5.55 kWh/m³ (0.16 kWh/ft³), with the average being about 5.77 kWh/m³ (0.164 kWh/ft³). In Table 5.5 a value of 5.98 kWh/m³ (0.17 kWh/ft³) has been selected for the low value for the energy density. Based on the achieved performance with single laboratory cells, and the analogy with the lithium-metal sulfide battery subsystems, the high energy density which could be achieved within the next decade is estimated to be 8.83 kWh/m³ (0.25 kWh/ft³).

With the same assumptions for the power conditioning subsystem volume requirements as before, the total system is expected to exhibit energy densities within the range of 4.94 to 6.70 kWh/m³ (0.14-0.19 kWh/ft³), the lower value being based on present day technology.

The life of large capacity sodium-sulfur batteries has yet to be established. Although Table 5.3 indicates that greater than 200 cycles at about a 50 percent depth of discharge can be obtained with small cells, realistic values for batteries are harder to establish. One prediction is that a life of 2 to 4 years (500 to 1000 cycles) should be attainable⁽²⁰⁾. Ford⁽²¹⁾ has attained over 2000 cycles on some single cells at limited depths of discharge, but with an accompanying steady decrease in capacity attributed to the build up of

corrosion products. When metallic impurities are not present in the cells⁽²²⁾, this decrease is not observed. In view of the lack of data, a conservative estimate has been made in Table 5.5 of 2 years for the low value, and 5 years for the high value. Initial battery installations are expected to exhibit the lower values, unless the problems with corrosion and failure of the electrolyte materials can be resolved.

Cost Characteristics. Battery installations have not been built in size comparable to the requirements of an IUS. Until the various problems with each battery concept can be resolved, it will not be possible to finalize the cell and battery specifications for materials and performance. Without such detailed specifications it would be impossible to arrive at accurate costs for materials and fabrication. In this section data from available published literature, and discussions with manufactureres and other interested parties, have been used to derive cost estimates applicable to the IUS. Emphasis has been placed upon using existing cell designs, battery designs, and available materials/equipment because of the interest in near term (1975-1985) implementation. The cost data in many cases are higher than would be predicted on a long-term development program. Some of the cost data summarized earlier in Table 5.2 reflect these optimistic estimates which cause the apparent wide variation among the different battery concepts.

Power Conditioning Subsystem. To meet the requirements for the IUS the electrical performance specifications for the power conditioning subsystem should be similar for each of the alternative battery concepts.

In Reference 1 the anticipated range of capital cost is given as 72 to 80 \$/kW, with the former value assigned to equipment which may be available before 1985, while the latter applied to equipment ordered today. More recent data⁽²³⁾ have substantiated these estimates. For near-term applications, e.g., the installation of a PbO_2/Pb storage system, the costs have been estimated at 70 to 80 \$/kW; while, for the long term, e.g., the use of Na/S or Li/MeS batteries, the costs have been estimated at 60 to 70 \$/kW. Reference 6 is less specific about the discussion of capital costs; but, it indicates that power-related capital costs, which would include those for power conditioning, would lie in the range of 50 to 100 \$/kW.

For the present study, a value of 80 \$/kW has been assigned for systems installed before 1980 (i.e., the PbO_2/Pb or the $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery concepts). For systems installed later in 1980-1985 (e.g., Na/S or Li/MeS battery concepts) the cost may decrease to about 70 \$/kW (1975 dollars).

Lead-Acid Battery. The various types of lead dioxide-lead batteries are manufactured by mass-production techniques today, and realistic cost data are available which can serve as a guide for projecting the cost of an IUS storage battery.

Small capacity PbO_2/Pb batteries such as used in automobiles, may cost between 20 and 30 \$/kWh⁽²⁴⁾. The larger, heavy duty traction batteries cost in the range of 48 to 80 \$/kWh. Large submarine batteries are expected to cost between 50 and 150 \$/kWh, depending on size⁽⁶⁾. The range of 50 to 80 \$/kWh for conventional PbO_2/Pb batteries is believed to be realistic for scaling up to the size for an IUS application. For early installations the higher value should be selected, as shown in Table 5.6. At a value of 35 wh/kg (15 wh/lb) as given in Table 5.2, the above cost range would be equivalent to a battery manufacturing cost of between 1.38 and 2.20 \$/kg which is typical of present day manufacturing costs.

If a PbO_2/Pb installation was specifically designed and manufactured for a load-leveling or peaking application, some economies should result, and the storage-related capital cost could be smaller. References 3 and 24 summarize the performance and cost objectives for such an "improved" PbO_2/Pb battery. The latter reference predicts that battery material costs can be reduced by a factor of 2.5, while battery costs can be reduced by a factor of 1.5 to 2. It was assumed that 5 kW, 50 kWh cells could be built within an envelope of 0.61 x 0.61 x 2.1 x weighing about 905 kg (1991 lb), and costing about 10 \$/kW for materials for each cell. Since the cost of a battery is typically about twice the materials cost, such a battery might cost about 20 \$/kWh. Other estimates have not been as optimistic and have ranged from 30 to 40 \$/kWh.

TABLE 5.6. SUMMARY OF CAPITAL COST CHARACTERISTICS OF
CANDIDATE BATTERY CONCEPTS FOR IUS APPLICATIONS

Battery Concept	Storage Related Capital Cost, \$/kWh		Balance of Plant Cost, \$/kW		Installation and Start-up Cost, \$/kWh		Power Conditioning Subsystem Cost, \$/kW	
	High	Low	High	Low	High	Low	High	Low
PbO ₂ /Pb	80	40	35	25	15	12	80	--
Zn/Cl ₂ ·6H ₂ O	40	20	35	25	15	12	80	--
Li/MeS	48	32	10	5	10	5	80	70
Na/S	48	26	10	5	10	5	80	70

Note: "High" values refer to projected costs if installation were to occur within the next five years. "Low" values refer to projected costs if installation were to occur between 1980 and 1985 (1975 dollars).

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If it is assumed that large scale manufacture of improved batteries brings the cost down to 1.10 \$/kg, then from the battery design weight given in Reference 3 a value of 40 \$/kWh may be calculated. Similarly, if the energy density of improved PbO_2/Pb batteries is increased to 55 Wh/kg then at \$1.10/kg a value of 40 \$/kWh may also be calculated. Some prototype batteries today⁽²⁵⁾ already have energy densities in the range of 44-50 Wh/kg; therefore, with a substantial R&D effort it may be possible to achieve 55 Wh/kg within the next decade.

Thus, a more conservative, more easily justified capital cost estimate for improved PbO_2/Pb batteries could be 40 \$/kWh and this value has been included in Table 5.6. In the long-term, beyond 1985, the cost could be further reduced, and values as low as 25 to 35 \$/kWh might be achieved.

The balance of plant referred to in Table 5.6 include such items as the ventilation, safety and control equipment, the buswork, and heat exchanger devices, where applicable. For the PbO_2/Pb battery concept this capital cost item is expected to amount to 25 to 35 \$/kW for the near term.

The installation and start-up costs can only be estimated from the commissioning of other electricity generating equipment at the present time.⁽²³⁾ For battery systems of a size suitable for the IUS application these costs are expected to be between 12 and 15 \$/kWh for a large total installed capacity. For simple systems or demonstration systems these costs could be higher, and amount to as much as 30 \$/kWh.⁽²³⁾

Zinc-Chlorine Hydrate Battery. When this battery concept is mass produced and materials produced in bulk, the developers⁽⁹⁾ predict that the energy storage related capital cost will lie between 10 and 20 \$/kWh. This is a 10- to 20-fold reduction over the present reported costs for prototype batteries (Table 5.2) of up to 50 Wh capacity. Another estimate⁽²⁶⁾ has been 25 to 30 \$/kWh for mass produced batteries.

Details of the construction and materials incorporated in the $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery have not been published; but, in certain aspects this battery is similar to the zinc-air battery with flowing electrolytes. Typical manufacturing

costs for zinc-air batteries are 3.30 to 7.27 \$/kg. Table 5.2 gives an average value of 110 Wh/kg for the energy density of $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ batteries. From these data a manufacturing cost of between 30 and 66 \$/kWh can be derived as a rough estimate.

Considering all the above estimates, it is anticipated that the first generation of $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ batteries will cost about 40 \$/kWh; but, there is good indication that within the next decade the cost could fall to about 20 \$/kWh, as shown in Table 5.6. The balance of plant costs shown are expected to be similar to those of the PbO_2/Pb battery, which also operates at near ambient temperatures. While less safety and ventilation equipment may be required with the $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery (because only the cell stacks need to be located in a building⁽⁴⁾), the amount of auxiliary equipment is extensive for this battery type. Therefore, in Table 5.6 a similar range of costs is given as for the PbO_2/Pb battery.

Installation and start-up cost data are not available. Start-up is anticipated to be a little more complex than for the PbO_2/Pb battery because of the need to initiate the refrigeration cycle for the chlorine hydrate; but, installation cost is expected to be less. Overall, the total installation and start-up cost for a $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery subsystem may be similar to that for the PbO_2/Pb subsystem, namely 12 to 15 \$/kWh.

Lithium-Metal Sulfide Battery. This battery type is still being developed, and several possible designs exist, utilizing many types of materials. Although final design and materials specifications have not been chosen, one manufacturer has published preliminary cost data⁽¹²⁾ based upon present state of the art. These data, summarized in Reference 5, show that laboratory scale cells currently cost about 2130 \$/kWh; but, the projection for cells produced on a pilot plant scale is about 130 \$/kWh, based upon materials costs. Only when the cells are mass produced is the cost expected to fall to about 16 \$/kWh. In comparison, various cost goals published for this battery have been between 12 and 25 \$/kWh, the higher cost being associated with a longer life battery. Using as a guideline the fabrication cost scale-up factor of 2 to 3 times, which is common practice in the PbO_2/Pb battery industry, and the lowest

estimated materials cost of about 16 \$/kWh, the cell costs will fall in the range of 32 to 48 \$/kWh. Battery costs are likely to be closest to the 48 \$/kWh value. From the above estimates, considerable effort will be required before the cost goals can be approached for this battery.

Other estimates of battery costs can be made from published data. Reference 27 gives a value of 5.63 \$/kg for Li/MeS batteries, while Reference 28 gives 6.60 \$/kg. The average is 6.12 \$/kg (2.78 \$/lb). In Table 5.2 the energy density is given as 147 Wh/kg for single cell data, while data in References 13 and 14 for (1 MW, 10 MWh) design projections yield values of about 127 Wh/kg for the AI battery and 119 Wh/kg for the ANL battery. The average value is 130 Wh/kg, hence the energy storage cost is calculated to be 47 \$/kWh.

Based upon this estimate, and the other estimates generated above, it is concluded that if Li/MeS batteries are produced in relatively large quantities then over the next decade the storage related capital cost will not be below 32 \$/kWh, and will approach about 48 \$/kWh for the first installations.

The balance of plant costs for the high-temperature batteries are expected to be less than for the two low operating temperature alternatives previously discussed. There will be a need for a ventilation/heat exchanger/fire control system, and a safety and data acquisition system as before, but there is no electrolyte to recirculate, heat, cool, or filter. Temperature control of the operating Li/MeS cells will be easier, and if the cells are insulated for safety reasons, then some or all of the heat generated during cycling can be used to maintain the cells at temperature. The heat exchanger may be most severely loaded if and when it is used to bring the batteries up to temperature after initial installation, or after repairs/replacements. In Table 5.6, therefore, a range of 5 to 10 \$/kW has been given the balance of plant cost.

The high temperature batteries are expected to be delivered in the form of prewired and engineered modules, and connecting the various modules together should be relatively easy. Hence the installation cost is expected to be less than for the PbO_2/Pb and $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ batteries. Although the cell stacks in

the $\text{Zn/Cl}_2 \cdot 6\text{H}_2\text{O}$ will be in modular form, the balance of plant is expected to take longer to install, and start-up is expected to be more complex. Thus installation and start-up costs for Li/MeS battery types are expected to total about 10 to 15 \$/kWh.

Sodium-Sulfur Battery. Preliminary cost estimates have been presented by GE for cell materials and fabrication^(6,29). At the present time, prototype cells cost about 16,683 \$/kWh to fabricate, including a materials cost of about 1683 \$/kWh. The stated objective⁽⁶⁾ is a materials cost of 1.24 \$/kWh, and a battery module cost of 6.74 \$/kWh. However, the current collector being used today is graphite felt, which at 156 \$/kg is equivalent to approximately 10 \$/kWh⁽⁶⁾. There is no strong indication that this cost will be significantly decreased, and presently no inexpensive, noncarbon alternative has been identified. Some battery developers are looking at reticulated vitreous carbon as a current collector, and this is expected to cost about half as much as graphite felt on a \$/kWh basis. Others are looking at carbon powders. Nevertheless, there is serious concern as to the achievement of projected low cell costs in the near future. With this thought in mind, Reference 29 quotes a cost projection of 12 to 18 \$/kWh for the cells. TRW projects⁽³⁰⁾ that costs will be above 10 \$/kWh for their cells.

Table 5.2 suggests that the manufacturing cost of Na/S cells is \$2.20/kg or greater. Battery module designs prepared for possible evaluation in the BEST Facility indicate that there will be between 5.9 and 7.3 kg/kWh. On this basis the minimum cost of manufactured cells will be in the range of 13 to 16 \$/kWh. Less optimistically, Reference 31 cites manufacturing costs of between 4.40 and 6.60 \$/kg for the Ford Na/S cells assembled into small batteries. Therefore, the cost of load-leveling or peaking batteries is not expected to be below 26 \$/kWh and could be as high as 48 \$/kWh. These values are more in line with cost data estimates presented in Reference 17 for Na/S traction batteries. At an energy to power ratio of 1, costs (in 1973 dollars) were expected to range from 42 to 70 \$/kWh. At an energy to power ratio of 3 these costs ranged from 30 to 70 \$/kWh for a discharge efficiency in excess of 80 percent. Values of 26 and 48 \$/kWh have been chosen as the "low" and "high" values for the storage-related capital costs given in Table 5.6.

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As mentioned earlier, the balance of plant costs are thought to be similar to those for the Li/MeS battery installation, namely 5 to 10 \$/kWh. The installation costs of the Na/S battery modules are also thought to be similar to the estimate made for the Li/MeS battery subsystem, i.e., 5 to 10 \$/kWh of installed capacity.

Miscellaneous Costs. Other cost characteristics of interest are (1) the operating and maintenance costs, (2) the net replacement capital costs, (3) the salvage values, and (4) any credits which arise from operations. Because these battery energy storage concepts have yet to be built, the values shown in Table 5.7 represent very rough estimates assembled for this study.

Operating and Maintenance (O&M) Costs. The maintenance requirements for the PbO_2/Pb and the $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery systems are expected to moderate; while, the requirements for the Na/S and Li/MeS battery systems are expected to be low. The O&M costs for the latter battery concepts have been often quoted in the range of 0.5 to 1.0 mill/kWh by utility companies^(32,33) and by battery manufacturers^(3,6). The higher value is taken as representative of 1975 costs, as indicated in Table 5.7. For the PbO_2/Pb and $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery systems, whose maintenance will be required more frequently because of the nature of the battery chemistry and complexity of the systems, the O&M costs will be higher. A value of 3 mill/kWh has been assigned to the PbO_2/Pb battery system, and a value of 2 mill/kWh to the $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery system.

Net Replacement Capital Costs. The estimated trends in battery related capital costs (1975 dollars) is shown in Figure 5.2. Using the curves presented in this figure, and the estimated life of the batteries shown in Table 5.6, a replacement capital cost schedule is presented in Table 5.8. By the year 1995 it is anticipated that there will be only relatively small decreases in the cost of a given battery, but performance and life will be considerably improved.

Salvage Values. Salvage costs for the PbO_2/Pb batteries are expected to be between 10 and 20 \$/kWh of installed capacity. The difference between the salvage value and the replacement costs reflect refabrication, materials separation and purification, and wastage (both as part of the refabrication procedure, and due to non-reusable materials).

TABLE 5.7. SUMMARY OF OTHER COST CHARACTERISTICS OF
CANDIDATE BATTERY CONCEPTS FOR IUS APPLICATION

Battery Concept	O&M Cost \$/kWh	First Replacement Capital Cost \$/kWh	Salvage Value \$/kWh
PbO ₂ /Pb	0.003	56	10-20
Zn/Cl ₂ ·6H ₂ O	0.002	29	15-30
Li/MeS	0.001	44	10
Na/S	0.001	43	5

Note: Additional replacement capital costs are summarized
in Table 5.8, and the schedule shown in Figure 5.2.

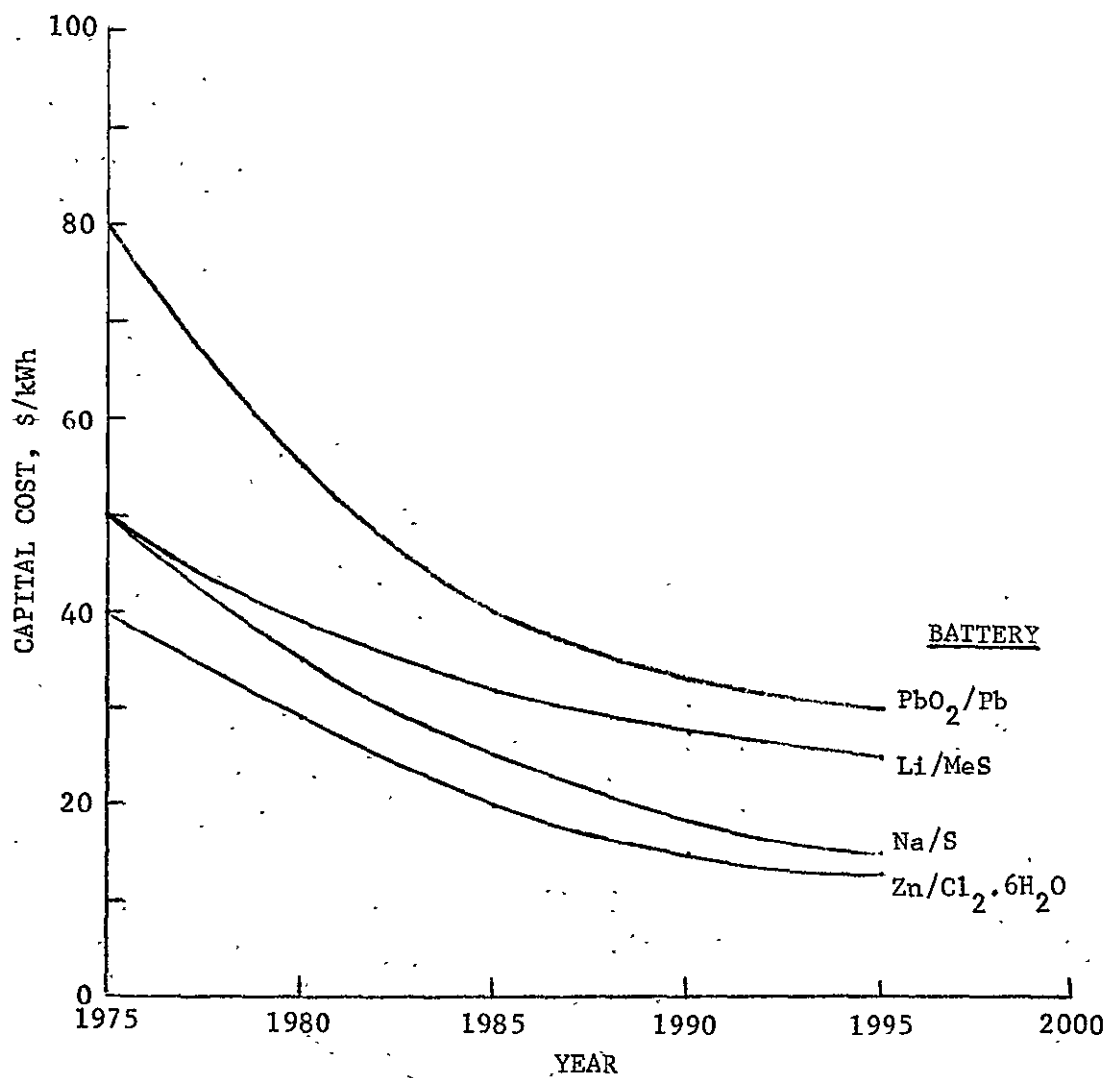


FIGURE 5.2. 20-YEAR PROJECTION OF CAPITAL COSTS FOR BATTERY ENERGY STORAGE SUBSYSTEMS

TABLE 5.8. ESTIMATED BATTERY REPLACEMENT COSTS AND SCHEDULE

Battery Concept	Years After Installation																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PbO ₂ /Pb	80					56					40					34					
Zn/Cl ₂ ·6H ₂ O	40					29					20					15					
Li/MeS	48		44			39					32					28					26
Na/S	48		43			36					26					19					16

NOTES: 1975 is assumed to be the date of the original installation. The power conditioning subsystem is expected to have a life of 20 years or more. Costs, in 1975 dollars, expressed as \$/kWh. Installation costs and salvage values not included.

For $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ batteries most of the salvage value is thought to reside in the titanium and the noble metal catalysts, if these are incorporated into mass produced cells. A value of 15 to 30 \$/kWh has been assigned to this battery subsystem.

The salvage values for the high operating temperature batteries are considered to be smaller than the above, and even negligible in the case of Na/S batteries. For such batteries the materials of construction are readily available, and relatively inexpensive. It is not certain whether the ceramic electrolyte material can be reclaimed. Thus, only the feedthroughs and cell containers along with module structures and controls will probably be reused. A value of 5 \$/kWh therefore, has been assigned for Na/S batteries in Table 5.7. Similar comments can be applied to the Li/MeS battery subsystems. However, depending on the economic climate at the time, it may be desirable to recover and purify the lithium and the metal sulfides, as well as the cell containers and feedthroughs. An arbitrary value of 10 \$/kWh has been assigned to this battery type. It should be remembered that, at the present time, corrosion of the cell containers and of the positive electrode current collectors is a serious problem which results in contamination of the electrode materials and the electrolyte. In practice, therefore, if corrosion problems cannot be resolved, then it may be economically impractical to try and purify these contaminated cell materials.

Estimated Total Energy Storage Systems Costs. The cost data for each candidate battery concept and power conditioning subsystem are collected together to arrive at original (1975) installed and operating energy storage system costs. Four IUS applications have been selected to illustrate the total system costs. Each battery candidate is treated separately in Tables 5.9(A) through 5.9(D) and a round trip efficiency of 70 percent is assumed in calculating the installed capacity requirements for these various applications. The data are summarized in Table 5.10 along with similar estimates of what the total system capital costs might be if the IUS installation was delayed to 1985.

TABLE 5.9. SUMMARY OF ESTIMATED TOTAL ENERGY STORAGE CAPITAL COSTS
FOR CANDIDATE BATTERY CONCEPTS

IUS Application	Number of Generators Installed	Installed Capacity (a) kWh	Delivered Capacity kWh	Discharge Time hr	Battery Subsystem Cost (b) (d) \$/kW	Power Conditioning Subsystem Cost \$/kW	Installation and Start-Up Cost (d) \$/kW	Total System Cost (c) \$/kW
(A) PbO_2/Pb BATTERY CONCEPT								
1000-Unit Apartment	5	1,261	1,056	4	305	80	51	436
	4	4,878	4,065	7	466	80	81	627
Village Complex	7	3,798	3,179	2	139	80	20	239
	6	40,191	33,638	11	453	80	78	611
(B) $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ BATTERY CONCEPT								
1000-Unit Apartment	5	1,261	1,056	4	170	80	51	301
	4	4,878	4,065	7	251	80	81	412
Village Complex	7	3,798	3,179	2	87	80	20	187
	6	40,191	33,638	11	244	80	78	402
(C) Li/MeS BATTERY CONCEPT								
1000-Unit Apartment	5	1,261	1,056	4	172	80	34	286
	4	4,878	4,065	7	269	80	54	403
Village Complex	7	3,798	3,179	2	72	80	13	165
	6	40,191	33,638	11	261	80	55	396
(D) Na/S BATTERY CONCEPT								
1000-Unit Apartment	5	1,261	1,056	4	172	80	34	286
	4	4,878	4,065	7	269	80	54	403
Village Complex	7	3,798	3,179	2	72	80	13	165
	6	40,191	33,638	11	261	80	55	396

(a) Round trip efficiency of 70 percent assumed. Losses on hold assumed to be negligible.

(b) Includes storage related capital cost and balance of plant cost.

(c) This is the original installed capital cost, based upon 1975 cost estimates, for delivered capacity, and designed for maximum power discharge ratings.

(d) Based upon installed capacity and maximum discharge power ratings.

TABLE 5.10. ELECTROCHEMICAL ENERGY STORAGE CAPITAL COST
ESTIMATE BASED UPON PROJECTION FOR
1975 AND 1985

Battery Concept	Date of Original Installation	IUS Application (a)			
		1000-Unit Apartment Baseload Generation		Village Complex Baseload Generation	
		5 Generators	4 Generators	7 Generators	6 Generators
PbO ₂ /Pb	1975	436	627	239	611
	1985	280	386	173	377
Zn/Cl ₂ ·6H ₂ O	1975	301	412	187	402
	1985	213	218	147	272
Li/MoS	1975	286	403	165	346
	1985	210	284	134	278
Na/S	1975	286	403	165	396
	1985	190	252	126	247

(a) Round trip efficiency of 70 percent is assumed. Installed capital cost values in \$/kW (1975 dollars) based on maximum discharge rate in kW. Applications described in Table 5.9.

All of the cost data presented in Tables 5.9 and 5.10 have been presented on a \$/kW basis to facilitate comparisons with the costs of the prime mover/generator sets which are being replaced. This was accomplished by dividing the total cost of the energy storage system by the peak discharge rate for the particular IUS case being examined.

In terms of \$/kW (based upon the maximum discharge rate), Table 5.10 shows that low capital costs for battery energy storage systems accompany the shorter discharge times. Also apparent from Table 5.10 is the fact that a system incorporating PbO_2/Pb batteries will be the most expensive in terms of capital outlay, even though the lead time for installing this system may be the shortest. All the other alternative battery systems are similar in total costs, with the Na/S battery systems showing the greatest potential for minimizing the installed capital cost in the long term. However, it should be remembered that if a 20 year life is required, then the life cycle costs may change the relative merit of the alternatives.

If PbO_2/Pb batteries are considered to represent existing technology; $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ batteries near-term technology and Li/MeS or Na/S batteries long-term technology, then the installed capital cost data for a 70 percent efficient system may be summarized as shown in Table 5.11. The near-term (1985) data for the $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ battery were taken from Table 5.10 along with the 1975 data for PbO_2/Pb batteries. The averaged data for 1995 for Na/S and Li/MeS batteries were compiled from information given in Tables 5.6 and 5.9, and Figure 5.2.

Research and Development Opportunities

Because of the early stage of development of the candidate batteries discussed and the uncommon electrical requirements of the power conditioning subsystem, research and development opportunities of a wide variety exist. Only the more obvious problem areas are identified and summarized below. Additional information about R&D requirements can be found in many of the references listed at the end of this section.

TABLE 5.11. INSTALLED CAPITAL COST FOR AN ENERGY STORAGE SYSTEM
HAVING A ROUND-TRIP EFFICIENCY OF 70 PERCENT

Battery Concept State of Development	Application (a)			
	1000-Unit Apartment Baseload Generation		Village Complex Baseload Generation	
	5 Generators	4 Generators	7 Generators	6 Generators
Present (1975)	436	627	239	611
Near-Term (1985)	213	278	147	272
Long-Term (1995)	163	215	109	211

(a) Capital costs in \$/kW (1975 dollars) based on maximum discharge rate. Power conditioning subsystem costs in 1975-85 assumed to be 80 \$/kW; in 1995 70 \$/kW. Long-term projections based on averaged data for Na/S and Li/MoS battery concepts.

Power Conditioning Subsystem. Equipment to meet the specifications for the IUS applications are not necessarily off-the-shelf items. It is anticipated that until a significant market exists many of the components will be made to special order. Thus, the circuit breakers may typically be rated at 300 or 800 V, while it may be desirable to operate the storage system at 1000 volts. This is more a recognition of a need and meeting it, than a significant development effort.

Because of the nature of an electrochemical energy storage device the inverter can be sized differently from the converter to accommodate the different charge and discharge current and voltage requirements (maximum currents and voltages do not occur at the same time). Also, with an electrochemical system there will be a voltage transient at the beginning and end of charge and discharge. During discharge the voltage will slowly decay as the installed capacity is used up. Also, polarization losses vary with the rate of energy removal, and voltages will be lower as the power delivered increases. The accommodation of all these variables into power conditioning equipment having the desired characteristics will be a considerable task. For example, schemes could be devised for switching various battery modules in series and parallel in order to reduce the voltage range arising during charging and discharging portions of a cycle. In this manner a partial voltage range converter could be used instead of an expensive full range converter. Similarly, groups of modules could be connected to the load in sequence to minimize polarization losses, and ensure a nearly constant voltage (hence power output).

Materials for the DC buswork for the high temperature battery concepts may have to be developed. Standard electrical aluminum alloys cannot be used because of low tensile strength and high elongations at elevated temperatures.⁽²³⁾ Fully insulated copper may be desirable; but, this is a relatively expensive approach. Full insulation is required because of the possible build up of carbonaceous (conducting) contaminants in an air-cooled system. Use of an inert gas such as nitrogen or argon would prevent this build-up; but, this would increase operating costs.

Battery Storage Subsystem. In order to achieve the more optimistic capital costs previously cited, a considerable R&D program is necessary for each battery concept to develop (1) economical fabrication procedures for cell components, (2) economical assembly procedures for cells, (3) less expensive cell materials without sacrificing desirable properties, (4) economical procedures for assembling batteries and modules, including the auxiliary equipment such as controls and sensors.

The problems to be overcome are common to each battery concept⁽²⁸⁾ and may be summarized as follows: (1) low ratio of practical to theoretical energy density, (2) cell capacity losses with cycling, (3) corrosion of inactive components such as current collectors for positive electrodes and cell containers, (4) inadequate or too costly separator materials, (5) unavailability of adequate, inexpensive seals and feedthroughs, and (6) restricted availability or high cost of certain materials.

With PbO_2/Pb batteries a major concern is to improve the energy density and the utilization of the active materials. New grid designs, new paste and electrolyte formulations, and new packaging concepts may help to alleviate this problem. Another concern is to develop grid materials (especially for the positive electrodes) which will not corrode nor generate excessive amounts of gas. The latter, along with extended periods of overcharging resulting from poor charge acceptance, will increase O&M costs because more frequent watering ("topping") will be required. Ideally no watering should be necessary during the life of the battery. The grid materials developed must also be strong enough to withstand the creep which may occur as the plates become larger, paralleling the increase in cell size for energy storage applications. Dispersion strengthening may be one approach to obtaining desirable strength without introducing undesirable alloying (hardening) agents. The size of the battery modules and the duty cycle may mean that a considerable amount of heat has to be dissipated to prevent excessive temperature increases which shorten cell life. Methods of cooling these modules have to be devised, whether they rely on external heat transfer (e.g., air cooling) internal heat transfer (water cooled heat exchangers inside the cells) or a combination of these (e.g., recirculating the electrolyte through a heat exchanger). The latter approach may overcome the problem of electrolyte stratification during high rate discharges.

With $\text{Zn}/\text{Cl}_2 \cdot 6\text{H}_2\text{O}$ batteries the life of the inert electrodes has to be established, particularly the catalyzed electrodes used for the chlorine reactions. Improved methods for applying the catalysts need to be developed. A separator material is required with improved properties to reduce self-discharge and the parasitic currents occurring during cell operation. In this respect the effects of cell impurities and any corrosion products need to be determined. If improved performance can only be obtained in the absence of a cell separator the cell design needs to be optimized.

Improved container, separator and positive electrode current collector materials are needed for Li/MeS batteries. Porous iron, carbon powder, and vitreous carbon foam are being investigated as inexpensive substitutes for graphite felt as a current collector material. If porous iron is used in conjunction with FeS positive electrodes, the problem of excessive swelling of the latter during early discharges has to be overcome. Formation of the active materials before assembly, electrode additives, and varying particle size of the FeS powder have been suggested as approaches to the problem of swelling. Metal sulfide additives apparently increase cell performance, and this should be investigated further, along with the use of the new Al-Si negative electrode alloys. The development of flexible, low-cost separator materials would greatly facilitate cell assembly.

With the Na/S batteries, the problem areas are also corrosion of the cell container and the current collector in the positive (sulfur) electrode. Improved performance and life result through the use of materials of high purity, thus minimizing contamination. Hence low cost purification methods and corrosive resistant materials need to be developed. Improved fabrication procedures are also needed to give low cost, strong beta-alumina electrolyte materials of the desired shape, size and electrical properties. Cell designs could be modified to promote more even current density distribution over the electrolyte, which would favor longer life. However, problems with sodium wetting of the electrolyte are still being encountered.

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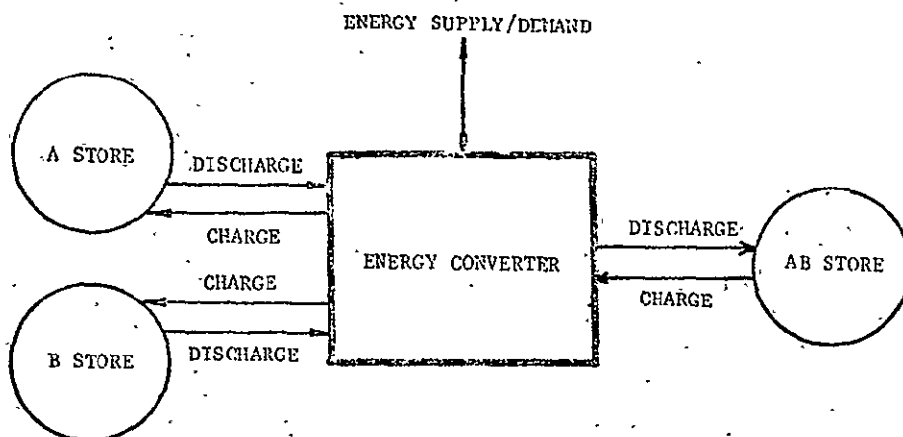
6. CHEMICAL ENERGY STORAGE

Basic Aspects of Chemical Energy Storage

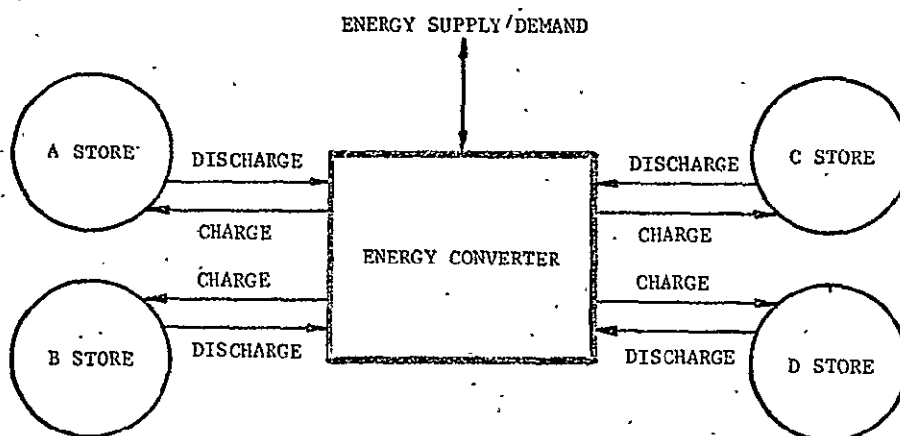
In the previous section concerned with electrochemical energy storage, energy was fed into an energy converter (i.e., the battery) within which chemical states of the reactants were changed. These "active" materials were then stored in the battery until a demand arose for recovery of the stored energy. As energy was withdrawn, the reactants reverted to their previous states. Such a description suggests that electrochemical energy storage is a special case of chemical energy storage; that is, (1) chemical energy is stored and recovered, and (2) the energy converter is also the energy store. For the general case of chemical energy storage, the energy stored is equivalent to the change in chemical bond energies.

Examples of chemical energy storage are shown schematically in Figure 6.1. The simplest case, indicated in Figure 6.1 (A), is exemplified by water decomposition. A more complex reaction is indicated in Figure 6.1 (B), which is exemplified by the Schulten reaction. Other specific reactions are cited in subsequent discussion. It should be noted that although the reactions are reversible to be of use for energy storage, they are not 100 percent efficient. It should also be noted that it is possible to utilize intermediate steps, with the regeneration of reactants to achieve a desired overall reaction at reasonable pressure and temperature levels.

The energy supply for charging a chemical energy storage device can be either electrical or thermal, and the energy converter can be either electrochemical or thermochemical to produce electrical output. Hybrid arrangements are also possible (e.g., electrical input hybridized with thermochemical converter through the use of an electrical heater). A possible integration of these energy converters in a chemical energy storage concept is shown in Figure 6.2. Conceptually, waste heat from a base load heat engine would be processed in a thermochemical converter. When system electrical demand is low, the excess electrical energy would



(A) REACTION $AB + E_1 \rightleftharpoons A + B$



(B) REACTION $A + B + E_2 \rightleftharpoons C + D$

FIGURE 6.1. SCHEMATICS OF SIMPLE CHEMICAL ENERGY
STORAGE CONCEPTS

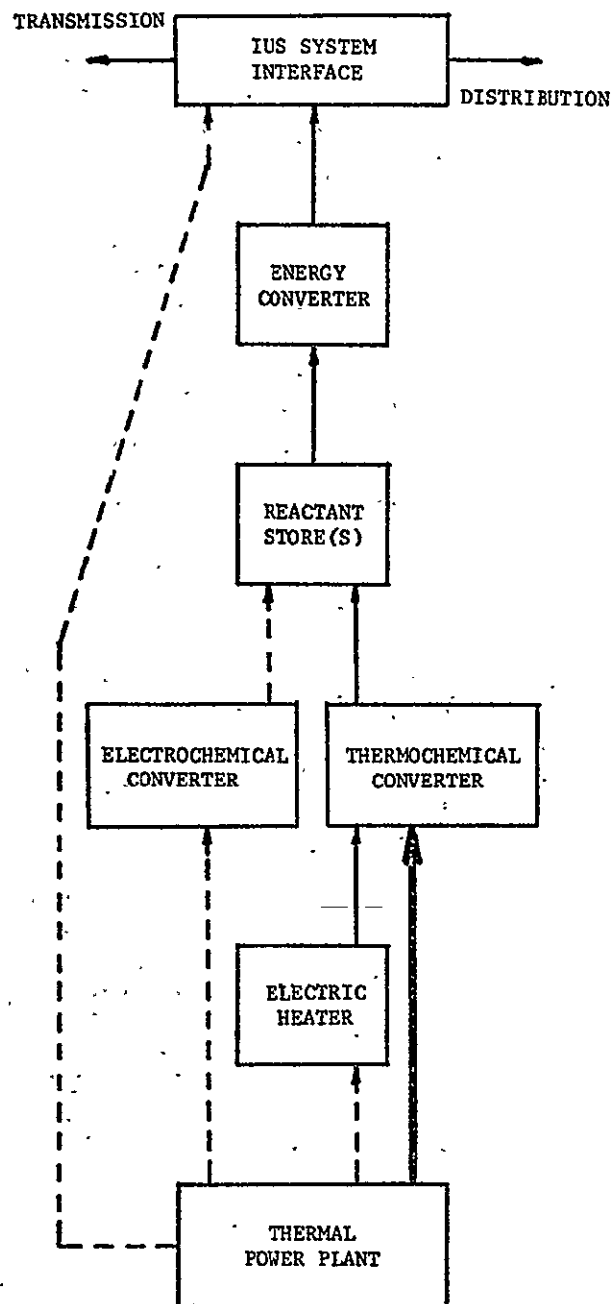


FIGURE 6.2. SCHEMATIC OF STORED ENERGY RECOVERY SCHEMES FOR INTEGRATED CHEMICAL ENERGY STORAGE SYSTEM

be stored in an electrochemical converter. The thermochemical converter is frequently a catalyzed device to improve reaction specificity and/or energy conversion efficiency. The electrochemical converter may be an electrolytic device that is also catalyzed and is used in conjunction with a fuel cell to recover the electrical energy.

It is convenient to divide a chemical energy storage concept into four subsystems. Referring to Figure 6.3 these subsystems are:

- A production subsystem in which one or more suitable chemical species are produced during charging
- A storage subsystem in which these chemical species are held until needed
- An energy conversion subsystem in which the chemical species are reacted during discharge to produce power
- A power conditioning subsystem that enables the storage equipment to be interfaced with user equipment.

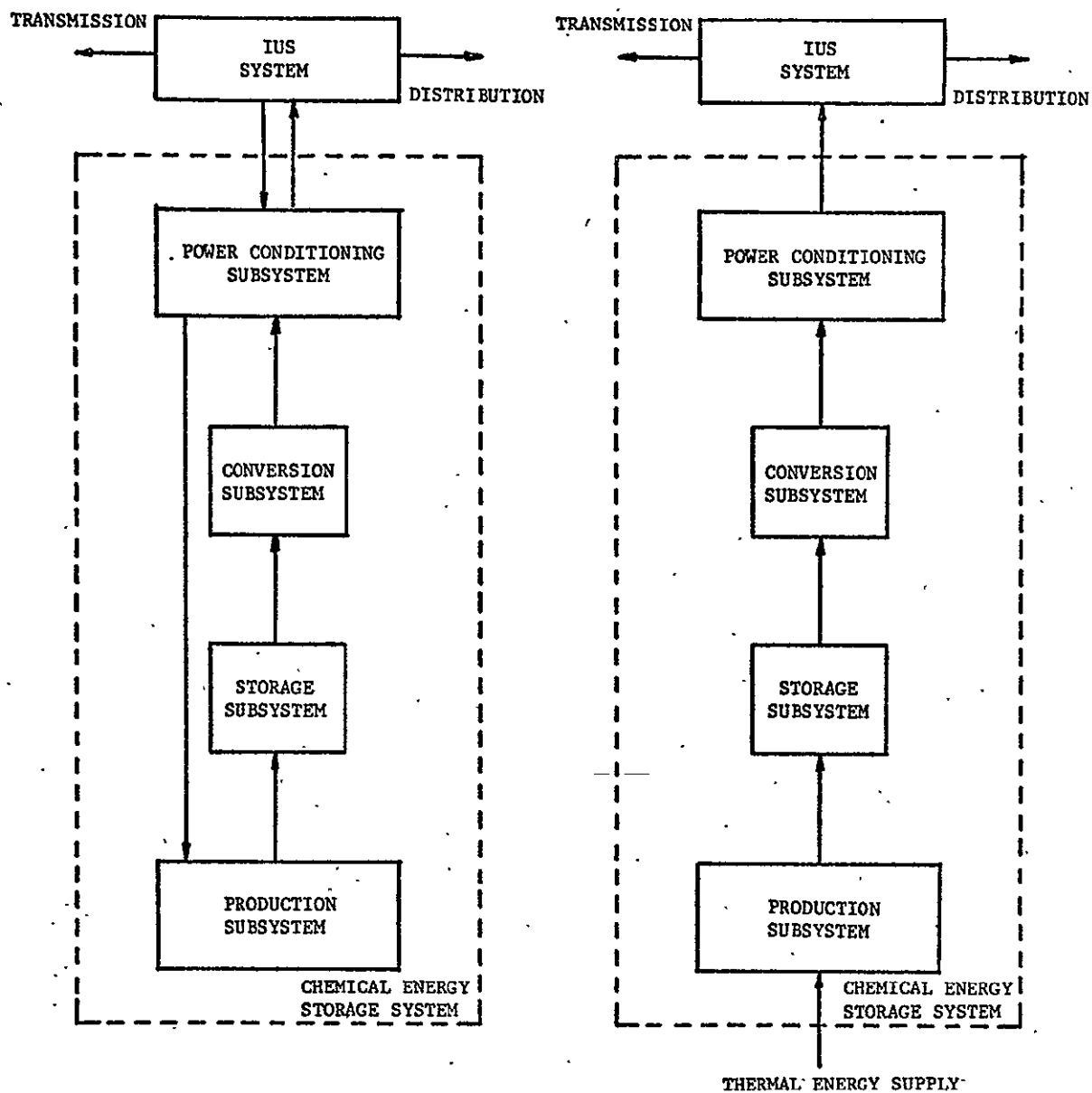
In Figure 6.3 (A) electrical energy is the primary energy source for producing the chemical energy carrier; while, in Figure 6.3 (B) thermal energy is the source.

A proof-of-concept demonstration for operational feasibility can be cited in the small-scale chemical energy storage installation at the Maplewood Laboratories of the Public Service Electric and Gas Company⁽¹⁾. This concept utilizes an electrochemical converter in the form of a TI modified water electrolyzer* to produce hydrogen, which is stored in a BNL metal hydride unit** for later recovery and use in a P&WA fuel cell*** of about 12.5 kW power rating.

* Teledyne Isotopes.

** Brookhaven National Laboratory

*** Pratt & Whitney Aircraft, Division of United Technologies Corporation.



(A) ELECTRICAL ENERGY INPUT

(B) THERMAL ENERGY INPUT

FIGURE 6.3. SCHEMATICS OF GENERALIZED CHEMICAL ENERGY STORAGE SYSTEMS

Alternative Concepts for Chemical Energy Storage

A variety of alternative techniques can be considered for each of the major subsystems (production, storage, conversion, and power conditioning) that make up a chemical energy storage concept. These subsystem techniques are summarized in Table 6.1.

Production Subsystem. In Table 6.1, seven techniques are identified for the production of chemical energy carriers. Each of them are presently in various stages of technical development.

Electrochemical Methods. A well-known technique* for chemical energy carrier production is electrolysis of water in which electricity is used to dissociate water into hydrogen and oxygen at relatively low temperatures and pressures and with relatively good efficiency (up to ~ 65 percent electrical efficiency).

The principal features of the electrolysis technique include:

- Noncorroding vessel containing an electrolyte solution in which pairs of electrodes are immersed
- Acidic (e.g., H_2SO_4) or alkaline (e.g., KOH) electrolyte with a deionized/demineralized water feedstock
 - Electrolyte is not consumed during electrolysis
 - Water may require replenishment to compensate for evaporation loss in some designs
 - Electrolyte solution may be circulated
- Electrode materials depend on
 - Type of electrolyte
 - Temperature/pressure levels of operation
 - Desired efficiency
 - Cost

* See Reference 2 for a review of this technology.

TABLE 6.1. LIST OF SUBSYSTEM TECHNIQUES CONSIDERED FOR
CHEMICAL ENERGY STORAGE

Subsystem	Specific Techniques Considered ^(a)
Production	Electrochemical (Electrolysis) Thermochemical Reactions Combined Electrochemical/Thermochemical Reactions Chemical Reactions Thermal Dissociation of Water Photochemical Reactions Biochemical Reactions
Storage	Mechanical (Pressurized Vessels, Natural and Man-Made) Cryogenic (Liquid) Chemical (Compounds Containing Hydrogen)
Conversion	Thermochemical (Gas Trubine, Combustion Chambers) Electrochemical (Fuel Cell)
Power Conditioning	(See Discussion in <u>Section 5</u>)

(a) This list does not consider applicability of the specific schemes. Considerations of near-term applicability will eliminate many of them, as discussed in the text.

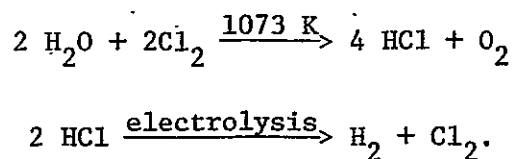
- Separator to separate hydrogen collected at the cathode from oxygen collected at the anode until removed from the cell.

Cells may contain multiple electrode pairs connected in parallel to form a unipolar or tank type electrolyzer. Cells can also be ganged in series to form bipolar or filter-press type electrolyzers having a desired generating capacity. As indicated in Reference 23, each arrangement has advantages/disadvantages that do not characterize general superiority of either one. Advanced electrolysis methods are discussed in References 2-6.

Recent interest has been expressed⁽⁴⁾ for incorporating water electrolyzers into "hydrogen economy" system concepts in which the hydrogen produced would serve as the energy carrier. The anticipated availability of economical off-peak electricity from nuclear base load generation enhances the attractiveness of this idea.

Electrolyzers, like storage batteries, can be operated over a wide range of conditions (voltage, current density, temperature, pressure), depending upon material limitations (e.g., relative electrocatalytic activity of electrodes, duty cycle). Electrochemical systems tend to polarize as operating current density increases; the results are increased voltage losses and decreased efficiency.

Thermochemical and Combined Thermochemical/Electrochemical Reactions. In this class of chemical energy storage concepts are those which use a water feedstock in a chemical dissociation reaction at elevated temperature to produce hydrogen and oxygen. The process occurs with the assistance of an intermediary compound that participates in a series of reactions but is recovered intact at the end of the process. The Reverse Deacon process is an example in which chlorine is the intermediary in the sequence:



Capital estimates of about 4.50 to 5.50 dollars per 10^6 Btu of hydrogen produced⁽¹³⁾ are thought to be typical of those thermochemical production schemes which are relatively simple. Capital costs will rise as the number of reaction steps increases, along with the possible associated complexity of materials handling and separation (especially if aggressive reactants dictate the use of expensive corrosion resistant materials and equipment). Using a conversion factor of 293 kWh per 10^6 Btu, then the energy storage-related capital cost range for thermochemical production subsystem processes is expected to be about \$30 to \$40 per kWh equivalent of hydrogen.

Chemical Reactions. Unlike many classes of production schemes, the purely chemical reaction is not constrained to use hydrogen as the principal energy carrier. Candidate reaction schemes are given in Table 6.2.

Thermal Dissociation of Water. Temperatures greater than 2273 degK (3632 degF) are needed to thermally dissociate water. This approach is within the capability of utilities operating nuclear reactors; but, it is clearly beyond the reach of the IUS.

Photochemical Reactions. In principle, photochemical reactions are simple and utilize solar irradiation as the energy source. A typical conceptual approach⁽¹⁸⁾ is to generate dc current photoelectrically and use it for water electrolysis. Another method is photolytic production of hydrogen^(13,36,37), which presently is very inefficient (120 hours of sunlight to produce 10^{-8} moles of hydrogen and oxygen).

Biochemical Reactions. Biochemical reactions directed at producing combustible gases have been reviewed in References 3 and 19. Examples of schemes studied on a laboratory scale include:

- Hydrogen production by certain anaerobic bacteria.
- Hydrogen production by nitrogen-fixing blue/green algae in the absence of nitrogen - but in the presence of sunlight.

TABLE 6.2. . CANDIDATE CHEMICAL REACTIONS FOR PRODUCTION
SUBSYSTEM

Reaction Scheme	Operating Temperature Range, degK
$\text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3\text{H}_2$	700 - 1200
$\text{CH}_4 + \text{CO}_2 \rightleftharpoons 2\text{CO} + 2\text{H}_2$	700 - 1200
$\text{C}_6\text{H}_{12} \rightleftharpoons \text{C}_6\text{H}_6 + 3\text{H}_2$	500 - 750
$\text{C}_7\text{H}_{14} \rightleftharpoons \text{C}_7\text{H}_8 + 3\text{H}_2$	450 - 708
$\text{C}_{10}\text{H}_{18} \rightleftharpoons \text{C}_{10}\text{H}_8 + 5\text{H}_2$	450 - 700
$\text{C}_2\text{H}_5\text{Cl} \rightleftharpoons \text{C}_2\text{H}_4 + \text{HCl}$	420 - 770
$\text{COCl}_2 \rightleftharpoons \text{CO} + \text{Cl}_2$	550 - 1000

- Hydrogen production by some photosynthetic bacteria in a limited-nitrogen environment.

Low production rate and gas separation requirements appear to be the key problems for these biochemical mechanisms.

This subsection on production subsystems is concluded with a comment on the large volumes of oxygen that would also be produced during water electrolysis. Oxygen could be sold to obtain a system credit; but, lacking a consumer, it must be discharged or stored (e.g., chemically) for subsequent use as an oxidizer in the conversion subsystem.

Storage Subsystems. As previously indicated in Table 6.1, three techniques for storing chemical energy carriers are considered: (1) mechanically in compressed gas form, (2) cryogenically in liquid form, and (3) chemically in combined form.

Gas Storage in Pressure Vessels. Compressed gas storage in pressure vessels is an established technique. For example, storage of hydrogen at 16.6 MPa (2400 psia) is common practice for relatively small volumes. An interesting version has been suggested in the form of storage in transmission/distribution lines ("line-packing" technique), provided that variable transmission pressure (say between 3.45 and 6.90 MPa (500 and 1000 psia) is acceptable.⁽²²⁾ It would also be desirable to minimize the distance between the energy carrier gas source and the energy converter, since booster compressor stations are generally required at 100-160 km (65-100 mi) intervals^(11,14) to compensate for line losses.

There remain some unresolved problems concerning high pressure storage of hydrogen: (1) hydrogen embrittlement of storage vessel materials, and (2) thermomechanical fatigue induced by regular fill/discharge duty cycles. At Los Alamos Scientific Laboratory hydrogen has been stored at 24 MPa (3500 psi) without difficulty; but, at a storage pressure of 34.5 MPa (5000 psi) container wall cracking was encountered.⁽³³⁾ Although high strength steels are susceptible to embrittling attack, several materials (300-series stainless steels, titanium, Monel, and some aluminum alloys)

have been found suitable for hydrogen service.⁽²⁴⁾ Pressure vessels wound from fiberglass reinforced epoxy resin show great promise, although wall permeability to hydrogen has not been established.⁽³⁵⁾

Other methods that have been suggested for gas storage in a hydrogen economy include underground caverns, aquifers, depleted gas wells, and submerged bladder devices.⁽⁴⁾

Within the limitations posed by storage vessel material strength, there is an inherent technical trade-off between: (1) high storage pressure and low volume and (2) high pressure and low deliverability; furthermore, there is a companion economic trade-off between cost of compressor and cost of storage container. For hydrogen service the regenerative compressor may offer advantages (e.g., an order of magnitude greater head coefficient) over comparable conventional multistage compressors. However, its efficiency is quite low (50 percent), and it is presently used at low specific speeds.⁽²⁾

Liquid Storage. There are definite size advantages to storing working fluids (particularly light gases such as hydrogen) in liquid form. For example, an 850-to-1 reduction in storage volume is realized by liquefaction of hydrogen. Since liquid hydrogen is cryogenic, achieving this volume reduction requires using to advantage already well-developed, specialized refrigeration, insulation, handling procedures, and accepting their associated costs (e.g., 1-2 $\$/10^6$ Btu for liquefaction versus 0.15-0.50 $\$/10^6$ Btu for compression⁽³²⁾).

Because the "hold" portion of the energy storage application cycle is relatively short (hours vs. days), it may be possible to simplify the liquid hydrogen storage vessel insulation techniques (and thus lower capital costs) by accepting higher levels of heat leakage and consequent hydrogen boil off. Perhaps an adaptation of LPG/LNG storage techniques will be appropriate.

Hydrogen can also be stored in multiphase form--"slush"-- but under more demanding conditions. Thus, this technique is rejected from further consideration.

Storage of other gases/liquids, as may be required for the use of some chemical/thermochemical production schemes, is well within established state-of-the-art technology and needs no elaboration. The principal design problems are generally posed by reactant corrosiveness.

Gas Storage in Chemically Combined Form. In addition to the compressed gas and liquified gas methods for storing large volumes of gas generated by a production subsystem, it has recently been found to be technically feasible to use chemical combination as a storage mechanism (with subsequent dissociation for recovery). For example, at the Phillips Laboratory, hydrogen has been stored by formation of rare-earth metal hydrides. At Brookhaven National Laboratory, simpler metal hydrides have been used. Engineering demonstration models have been operated, the largest of which has a hydrogen storage capacity of 7 kg (16 lb)⁽¹⁾. Various problems are under study, such as the effect of trace impurities (e.g., oxygen, water vapor) upon cycle life (rare-earth metal hydrides may be less susceptible than the simpler metal hydrides⁽³⁶⁾). Details of specific hydride storage systems are described in References 28-30.

Desirable features sought for a hydride storage concept include: (1) high retention capacity for hydrogen, (2) low dissociation temperature (<373 degK (212 degF), (3) high rates of absorption/desorption, (4) low heat of hydride formation, (5) high raw material density, (6) low cost raw materials, and (7) insensitivity to oxygen and water vapor. Systematic investigation of hydrides are being pursued, and several approaches have been identified for deriving improved materials: (1) alteration of interatomic spacing to allow placement of hydrogen in the octahedral as well as tetragonal interstitial sites; (2) use of glassy metals to increase intermetallic lattice spacing to allow placement of hydrogen in the more open space; (3) modification of dissociation temperature by alloying while still retaining hydrogen content; (4) increasing dissociation pressure by alloying to decrease the metal-hydrogen bond strengths; and (5) increasing dissociation pressure by increasing the entropy of the compounds.

Other combined forms of hydrogen storage can be considered--in both gaseous and liquid states. For example, ammonia storage/handling is a well developed practice. Other liquids include aromatic hydrocarbons (hydrogenerated during storage and dehydrogenerated during "discharge"^(15,31)) and fuels like hydrazine and methanol (both of which would be thermally decomposed during discharge).

Conversion Subsystem. Although the energy carrier released from storage can be converted into either heat or electricity, the intent here is to review the latter. In particular, the combustion engine (e.g., gas turbine)⁽³⁴⁾ and the fuel cell are appropriate conversion devices, and their applications can be readily illustrated with hydrogen as the energy carrier.

Gas Turbines. Hydrogen has many desirable characteristics as a fuel (high heating value, wide flammability range) and has been studied extensively in the 1950's for use in aviation gas turbines⁽³⁴⁾ and recently for use in reciprocating engines.⁽¹⁴⁾ Burned in air, it produces nominal hydrocarbon emission but its high flame temperature aggravates NO_x pollution. The latter problem could be eliminated if the oxygen from a water electrolysis production subsystem could be used as the oxidizer. Compared to a fuel cell, the hydrogen/oxygen gas turbine could be more expensive.⁽³⁴⁾

Fuel Cells. The fuel cell has been the subject of intensive investigation over the last two decades,^(4,22,31) much of it under the sponsorship of the U.S. space program. It is similar to a battery in component makeup; that is, it has an electrode pair, an electrolyte and an interelectrode separation device. It is, however, distinguishable from a conventional battery's functional operation in that the reactants are stored externally and must be circulated through the cell, which now serves as a reaction chamber. (Actually, the electrochemical conversion to dc power occurs at the inert electrodes within the cell.) Like the storage battery, fuel cells are electrically modular and thus can be aggregated to achieve desired energy/power levels.

In a hydrogen/oxygen fuel cell, the gases are not physically mixed, as in a conventional combustion process,⁽⁴⁾ but are ionized at the electrodes. The resulting soluble ions migrate through the electrolyte toward reactive encounters that produce water. Being an isothermal device, relatively high conversion efficiencies (in excess of 40 percent) are expected. For example, hydrogen/air cells typically exhibit 55 percent and hydrogen/oxygen cells approach 60 percent⁽⁴⁾ over a broad operating band (25-125 percent of rated power). Good load following characteristics are also reported. Efficient electrode materials are presently very expensive, as are the sophisticated fabrication procedures. Fuel cells with long life and low capital costs tend to exhibit inferior power performance.

At the present time two programs are being directed towards commercial exploitation of large scale fuel cell design.

- TARGET program - development of natural gas-fueled cells for domestic housing application
- Fuel Cell Group program - development of natural gas-fueled cells, a steam/methane reformer for hydrogen generation, and complementary power conditioning equipment for utility substation application (up to 26 MW rating).

Both programs are being conducted by Pratt & Whitney Aircraft Division of United Technologies, Inc. Exxon, Inc., in conjunction with Alsthom (France) is also performing fuel cell R&D to support potential commercial applications.

Power Conditioning Subsystem. In a chemical energy storage concept that features a gas turbine conversion, the power conditioning equipment would be functionally split into two parts: (1) ac/dc converter for the production subsystem; (2) conventional equipment associated with a gas turbine driven synchronous generator.

The power conditioning requirements for a chemical energy storage concept that employs fuel cell conversion are expected to be quite similar to those

for an electrochemical energy storage concept (i.e., combination inverter/converter; see, therefore, the discussion in Section 5).

Alternative Approaches for Implementation

Candidate Concept Selection. The large number of chemical energy storage concepts that could be assembled from the subsystems identified in Table 6.1 can be reduced to the more promising candidates for IUS application. This reduction is effected via several criteria.

- State-of-the-art advancement beyond mere conceptual stage--that is, experimentation has progressed sufficiently to support reasonable assessment of the feasibility for bulk energy storage
- Relatively high component operating efficiencies and effective allocation of cycle energy.

Application of the first criterion leads to rejection of photochemical, biochemical, thermochemical, and thermal dissociation of water techniques for energy carrier production. Application of the second criterion leads to rejection of liquid storage of the energy carrier (disproportionate allocation of cycle energy to refrigeration). Chemical production methods (most of which require hydrocarbon feedstock) can be rejected on the basis of the elevated operating temperatures that would require an external heat source.

Having performed this screening, the alternative approaches from which to synthesize energy storage concepts are reduced to the following:

- Production subsystem
 - Electrochemical (electrolysis)
- Storage subsystem
 - Mechanical (pressure vessel)
 - Chemical combination

- Conversion
 - Thermochemical (gas turbine)
 - Electrochemical (fuel cell)
- Power conditioning
 - Converter (for thermochemical).
 - Inverter/converter (for electrochemical).

The results are summarized in Table 6.3 in which a procedure was used similar to that for corresponding aspects of Section 5.

The results of the screening have also been categorized as immediate or near-term options in Table 6.4 to indicate anticipated trends in technology. Table 6.4 is consistent with the concept that electrical energy should be fed into the storage system, and extracted from it and the recent emphasis upon hydrogen as a chemical energy carrier.

Technical Characteristics. The technical characteristics of the production, storage and conversion subsystems will be discussed in some detail, and a brief mention made of the power conditioning subsystem. The characterization is based upon data presented in the open literature. Performance characteristics will change as the state of the technology advances.

Production Subsystem. Technical performance and cost data published in the literature, and obtained from electrolyzer manufacturers, are summarized in Table 6.5. It should be noted that the energy efficiency of laboratory cells, or small commercial units, can be very high, of the order of 90 to 95 percent. However, when these cells are scaled-up into commercial units of the sizes of interest to IUS technology, the efficiency is more typically 50 to 80 percent, and often about 60-70 percent.

Water electrolysis may be characterized by two cell voltages.⁽²⁾ One is the "reversible" voltage for electrolysis, below which dissociation of water is impossible. This has a value of 1.23 volts at zero current, atmospheric pressure, and 77 F (25 C), and has a negative temperature coefficient of

TABLE 6.3. INITIAL SCREENING SUMMARY FOR CHEMICAL ENERGY STORAGE SUBSYSTEMS

Subsystem	Technique (a)	Score					Overall Figure of Merit (c)
		Hardware Availability	Round Trip Efficiency	Service Life	Technical Merit (b)	Life Cycle Cost	
Production	Electrochemical	2	2	2	6	2	12
	Thermochemical	1	1	1	3	1	3
	Thermochemical -						
	Electrochemical	1	1	1	3	1	3
	Chemical	2	1	2	5	2	10
	Thermal	1	1	1	3	1	3
	Photochemical	1	1	1	3	1	3
	Biochemical	1	1	1	3	1	3
Storage	Mechanical	2	2	2	6	2	12
	Cryogenic	2	2	2	6	1	6
	Chemical	1	2	1	4	1	4
Conversion	Thermochemical	1	1	1	3	1	3
	Electrochemical	2	2	1	5	1	5

(a) See Table 6.1 and text.

(b) Sum of scores for hardware availability, round trip efficiency, and service life.

(c) Obtained by multiplying technical merit score by cost assessment. Highest score is 12, lowest is 3.

TABLE 6.4. CANDIDATE CHEMICAL ENERGY STORAGE CONCEPTS FOR IUS APPLICATION

System Concept	Implementation Time Frame	Subsystem		
		Production	Storage	Conversion
A	Immediate (1975)	Electrochemical (Water Electrolysis)	Mechanical (Compressed Gas)	Electrochemical (Fuel Cell)
B	Near Term (1985)	Electrochemical (Water Electrolysis)	Chemical (Metal Hydride)	Electrochemical (Fuel Cell)
C	Immediate	Electrochemical (Water Electrolysis)	Mechanical (Compressed Gas)	Thermochemical (Gas Turbine)
D	Near Term	Electrochemical (Water Electrolysis)	Chemical (Metal Hydride)	Thermochemical (Gas Turbine)

TABLE 6.5. PERFORMANCE AND COST DATA FOR WATER ELECTROLYZERS

Reference	Electrolyzer Type	Approximate Capacity, kg/hr of H ₂	Energy Efficiency, %	Electrical Requirement, kWh/kg of H ₂	Capital Cost, \$/kW ^(a)	Year
(22)	Commercial Cells	--	57-72	52.8	-95	1972
(39)	Commercial Cells	--	50-80	--	120	1972
(40)	Teledyne, Bipolar	4545	--	--	88-109	1973
(41)	Teledyne, Bipolar	0.68	50-80	--	120	1974
(42)	Commercial Cells	2273	70-80	--	-100	1974
(38)	Commercial Cells	--	85-90	--	70-100	1974
(43)	G.E. SPE Cells ^(b)	2045	92.5	--	-335 ^(c)	1974
(44)	Lurgi, High Pressure	795	--	50.6-55.0	-345 ^(c)	1974
(1)	Commercial Cells	2954	--	--	>300 ^(c)	1975
(45)	Brown Boveri, Bipolar	>59	--	48.4-57.2	145-215	1975

(a) Hydrogen output electrical equivalent.

(b) SPE = Solid Polymer Electrolyte.

(c) Installation, freight and insurance costs included.

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voltage. The other characteristic parameter is the "thermoneutral" voltage, which has a value of about 1.47 volts, under the same conditions, but has a slight positive temperature coefficient. Electrolytic production of hydrogen and oxygen is possible between 1.23 and 1.47 volts at 77 F (25 C) if heat is supplied to the system. At the thermoneutral voltage, the gases are evolved without the release of heat, but above 1.47 volts waste heat is evolved along with the gases.

At the thermoneutral voltage the energy efficiency is ideally 100 percent, but at the reversible voltage the energy efficiency can be 120 percent at STP (as given by the ratio of enthalpy to Gibbs free energy) provided heat is absorbed from the surroundings. Stated another way, the electrical energy required to dissociate water in theory is only 83.7 percent⁽⁴⁾ of the combustion (thermal) energy of the hydrogen gas produced. In practice, these high values can never be attained because in order to make the electrolysis reaction proceed at practical rates the polarization which results represents significant voltage losses. If V represents the operating cell voltage, and V_o the reversible cell voltage, then the polarization losses may be represented as follows:

$$V - V_o = V_a + V_b + IR$$

where I is the electrolysis current; R is the cell internal resistance; and V_a , V_b are the voltage losses due to efficiencies in electron and mass transfer at the anode and cathode.

Operating data supplied by Lurgi-Apparate Technik GmbH. for their Zdansky-Lonza "Electrolytor" pressure electrolysis modules (of the size of interest to the present study) indicate that about 51 to 54 kWh/kg (23 to 25 kWh/lb) of hydrogen produced are required, compared with a theoretical requirement of about 40.1 kWh/kg (18.2 kWh/lb) at NTP. Brown-Boveri electrolysis modules, based upon "Oerlikon" electrolyzers, require about 49 to 57 kWh/kg (22 to 26 kWh/lb), thus in terms of electrical efficiency the two types of commercial equipment are similar. The former, however, produce hydrogen and deliver it at about 30 atmospheres, hence if compressed gas storage is used, the compression requirements are lessened.

Both types of electrolyzers operate at about 1000 volts and 6600 amperes, although the current density, hence cell voltage, is governed by the cell design. The average operating electrical requirement is about 53 kWh/kg (24 kWh/lb), and the electrical efficiency is about 65 percent. The thermal or energy efficiency is about 77 percent (based on the lower heating value of hydrogen). These values are consistent with the other data given in Table 6.5, and represent the average state of the art. In Table 6.6, therefore, the value of 65 percent has been selected as the present day value anticipated for the electrical efficiency of the electrolysis production subsystem. Over the next decade the electrical efficiency of commercially available equipment could improve to about 77 percent (90 percent thermal efficiency). This is given as the high value in Table 6.6.

The range of 20 to 30 kWh/m³ (0.57 to 0.85 kWh/ft³) given for the energy storage density is based upon extrapolations of manufacturer's literature data for subsystems having a hydrogen capacity equivalent to 100 MWh delivered. The low value given refers to the electrolysis modules and auxiliary equipment alone, and does not include the storage subsystem. The latter is treated separately. With design optimization, and incorporation into a total energy storage system, the 50 percent improvement in energy storage density projected for the next decade should be attained.

Electrolyzers of the bipolar type incorporating conventional, nonnoble metal electrodes and asbestos separators, have been in operation for 10 years or more, with periodic maintenance. Unipolar types of electrolyzers have also established a good life expectation, with similar periodic maintenance, such as the replacement of the electrolyte, in which detrimental impurities collect. With continuing maintenance a life expectancy of 20 years or more can be expected from presently available electrolyzers, as shown in Table 6.6.

The high performance electrolysis cells being developed today, e.g., the Teledyne Isotope electrolyzers based upon Allis-Chalmers technology, and the General Electric SPE-cells, have yet to be scaled-up from laboratory cells

TABLE 6.6. TECHNICAL CHARACTERISTICS OF A PRODUCTION SUBSYSTEM

Subsystem Type	Thermal (Energy) Efficiency, %		Electrical Efficiency, %		Energy Storage Volumetric Density, kWh/m ³		Estimated Service Life, Years	
	High	Low	High	Low	High	Low	High	Low
Water Electrolysis	90	77	77	65	30	20	>20	10

Note: Efficiency refers to production of oxygen and hydrogen, and includes contributions from auxiliary equipment such as pumps, and dryers.

and small commercial units. These types of electrolyzers are much more complex in terms of hardware, monitoring and control equipment, and have not yet established a reputation for long life. If these types of electrolyzers are developed into efficient subsystems for energy storage applications, initially the life may only be in the range of 2 to 5 years.

Storage Subsystems. As mentioned earlier, two types of storage subsystems will be considered. For present day applications, and possibly near-term applications, compressed gas storage at 1000 psig is recommended. For possible installation within the next decade, provided the technical and cost projections are substantiated, storage of hydrogen as a metal hydride is suggested. The technical characteristics of both these subsystem alternatives are summarized in Table 6.7. A daily duty cycle is assumed for both alternatives in order to keep the capital cost of an installation as low as possible.

The efficiency of compressed gas storage can be high depending upon the efficiency of compression of the gases to be stored. Typically compressor efficiencies of 80 percent can be achieved for oxygen and 75 percent for hydrogen. If other losses are considered negligible then 75 percent would represent the low value for the thermal energy efficiency. However, there is some optimism for increasing efficiency. One approach might be to backpressure the electrolyzer production subsystem, i.e., produce the gases under pressure electrochemically, thus greatly (1) reducing the horsepower requirements for the compressors, (2) reducing the pressure differential, and (3) reducing the number of compression stages required. Efficiency values approaching 99 to 100 percent have been projected using this approach^(5,46) for the long term, and 97 percent for the near term⁽⁴⁶⁾. Reference 29 gives an efficiency of 98 percent for hydrogen compression to 2500 psig. If the oxygen is dumped, or delivered at low pressure for an alternative use, then conceivably an efficiency of about 98 percent might be achieved for storing the hydrogen gas, in this instance, and withdrawing it from storage when required. However, if back-pressurizing is used to achieve such high efficiency for the storage subsystem, a penalty in the form of a higher operating voltage for electrolysis will have to be paid in the production subsystem. A trade-off study may be advisable.

TABLE 6.7. TECHNICAL CHARACTERISTICS OF ALTERNATIVE STORAGE
SUBSYSTEM TECHNIQUES

Storage Subsystem Technique	Energy Efficiency, %		Energy Storage Density, kWh/m ³		Estimated Service Life, Years	
	High	Low	High	Low	High	Low
Compressed Gas Storage (Mechanical)	98	75	0.016	0.0094	20	5
Metal Hydride Storage (Chemical)	95	75	0.042	0.028	10	3

Notes: Efficiency estimates for storing and withdrawal of gases from storage. Storage subsystem assumed to be located close to production subsystem so that transmission losses are negligible. Daily duty cycles assumed so that no gases are lost during storage. An iron-titanium alloy is taken as the basis for computing the energy storage density.

Little data have been published concerning the operation and performance of metal hydride storage devices for energy storage applications. Some data are available from Brookhaven National Laboratory^(29,47), and some operating data have been made available informally by Public Service Electric and Gas Company⁽⁴⁸⁾ for their Maplewood Laboratories Test Facility. Both these sources of information refer to an iron-titanium hydride compound as the hydrogen storage medium. This material is relatively inexpensive, and the raw materials are readily available, hence this iron-titanium hydride alloy storage subsystem may be the most practical for near-term applications. The data in Table 6.7, therefore, refer to this particular hydride material in the storage subsystem.

Efficiencies as high as 95 percent have been measured for hydriding and dehydriding these small capacity (14 lb of H_2 , max.) devices. Hence the upper limit for large metal hydride storage devices, suitable for IUS applications, has been set at 95 percent. However, with scale-up of the prototype devices there is a problem with ensuring adequate mass flow and heat transfer through the alloy particle bed(s). BNL is addressing this problem of building large storage capacity modules, and have looked at three basic types of design so far (a) the conventional shell and tube, (b) the "cross-flow" design, and (c) the fluidized bed concept.⁽²⁹⁾ All three designs have some undesirable features, and the final storage design has not yet been selected. Other alternatives may be considered. In the meantime, it could be more realistic to assume that large capacity subsystems would have an energy efficiency of about 75 percent.

Whether the high efficiency values will ever be achieved may depend on economic rather than technical factors. Also such high values assumes that the storage subsystem is located near to the production subsystem, so that transmission losses are negligible. Also losses during "hold" times are assumed negligible, which may be true for a daily duty cycle. If these assumptions do not hold, then the efficiency obtained could be lowered by up to 10 percent from that indicated in Table 6.7.

For compressed gas storage subsystems, the energy storage density is based upon data from studies associated with Reference 49 wherein the hydrogen and oxygen were compressed to 1000 psig and stored in suitable steel vessels underground made from the largest available pipe with welded end-caps and manifolds. Because the volume of gases to be stored depends on the efficiency of utilization in the conversion subsystem, the energy storage density can vary, unless the gases are compressed by varying amounts for a fixed volume and given delivered energy. For example, with a fuel cell conversion subsystem working at 60 percent efficiency, and compressors working at 80 and 75 percent efficiency for oxygen and hydrogen, respectively, on a daily duty cycle the energy storage density would be about 14 kWh/m^3 (0.40 kWh/ft^3). If the fuel cell and compressor efficiencies are improved (corresponding to the "high" values shown in Tables 6.7), then the energy storage density might achieve a value as high as about 20 kWh/m^3 (0.57 kWh/ft^3). For the low values given for the efficiencies in those tables, the energy storage density is about 12 kWh/m^3 (0.33 kWh/ft^3). Hence, the range given in Table 6.7 is 0.33 to 0.57 kWh/ft^3 , in the absence of any other published data.

The energy storage density for a metal hydride subsystem will depend primarily on the hydrogen absorbing capability of the alloy, its density, and the subsystem efficiency, again in conjunction with the energy efficiency of the conversion subsystem. For the iron-titanium alloy devices the storage density is estimated to fall in the range of 35 to 53 kWh/m^3 (0.99 to 1.50 kWh/ft^3). The upper value is calculated from data given in Reference 48 for a 104 MWh device, and represents the anticipated state of the art in 1980, assuming a 100 percent storage efficiency. An efficiency of 75 percent is considered more realistic, which corresponds to a storage density of 40 kWh/m^3 (1.13 kWh/ft^3). However, if a device were to be built today, it would be far from optimized in terms of design and layout are concerned. Therefore, a more conservative value of 35 kWh/m^3 (0.99 kWh/ft^3) has been selected for the low value in Table 6.7. The range given, namely $35 - 53 \text{ kWh/m}^3$ (0.99 to 1.50 kWh/ft^3), is consistent with calculations made at BCL for other, but similar, applications.

The life of equipment associated with compressed gas storage can be in excess of 20 years, if it is well maintained and not abused. The limiting factor will be probably the life of the compressor seals, which could fail after only about 5 years of continuous, daily service. Until definite operating data are obtained under energy storage conditions, a safe estimate of subsystem life would be 5 to 20 or more years, with the lower value referring to present day applications.

Small laboratory-scale hydride storage devices have operated for about 1000 cycles⁽²⁹⁾, which is equivalent to about 3 to 4 years of operation on a daily duty cycle for an energy storage application. Maximum life has yet to be established for large modular subsystem units, hence a conservative estimate of 10 years has been given. During this time period it may be necessary to reactivate the hydride alloy bed, which in the case of iron-titanium alloys can become deactivated by traces of oxygen, water vapor and some hydrocarbons, for example, which originate in the compression stage.

Conversion Subsystem. For present day applications (Table 6.4) the fuel cell is the preferred conversion subsystem device; however, in the near-term gas turbines may become sufficiently well developed to merit consideration. Hence the latter will be briefly discussed also, although for IUS applications the fuel cell may be more suitable, or even a combined electrolyzer-fuel cell device (reversible fuel cell or reversible water electrolyzer). The latter concept is considered in detail in Reference 49, and discussed briefly below, because economic advantages can be seen in having one device electrolyze water to give hydrogen and oxygen during charging, and the same device act as a fuel cell to combine these gases on discharging.

The fuel cell is expected to exhibit a higher efficiency of operation than the gas turbine because of the removal of the Carnot cycle efficiency limitation. Pratt and Whitney Aircraft predict a value of 55 percent for a hydrogen-air fuel cell, and nearly 60 percent for a hydrogen-oxygen fuel cell.⁽⁴⁾ Reference 50 gives a range of 50 to 55 percent for a hydrocarbon

fuel cell supplied with hydrogen fuel, and air as the oxidant, while advanced hydrocarbon fuel cells are said to have an efficiency of 70 to 75 percent, indicating a potential for long-term improvement. However, unlike water electrolyzers, the enthalpy, Gibbs free energy and entropy terms are all negative for H_2-O_2 fuel cells, and in theory the upper efficiency limit is about 84 percent at 298 K (77 F) and atmospheric pressure.

Attractive electrolyte, high temperature (Bacon) hydrogen-oxygen fuel cells have performed at 62 to 68 percent efficiency, and Pratt and Whitney Aircraft cells at 63 percent efficiency⁽⁵⁾ for pressures up to 420 psia. General Electric solid electrolyte fuel cells have operated at 53 percent efficiency. Based on the above data, and data presented elsewhere,^(38,46,48,51) a low value of 50 percent has been given for the efficiency in Table 6.8. This value has been substantiated in a design⁽⁵⁴⁾ for a 1200 MWh H_2-O_2 fuel cell subsystem, and a 100 MWh H_2-O_2 fuel cell subsystem.⁽⁴⁹⁾ Over the next decade, if oxygen were to be used as oxidant, then efficiencies of up to 65 percent could be achieved. Higher values at low capital costs will only be achieved through significant R&D efforts on subsystem design and materials.

Predictions for the thermal efficiency of a gas turbine are similar, and like the fuel cell, depend on whether air or oxygen is used in the combustion process. If air is used in a converted fossil-fuel turbine^(50,52) the efficiency is likely to be about 30 to 35 percent. If a hydrogen air turbine were to be built an efficiency of about 40 percent has been predicted.⁽⁵⁾ With improved regenerator design, and the use of cooled turbine blades in conjunction with higher inlet temperatures, thermal efficiencies in the range of 55 to 60 percent should be possible in the long term. Hydrogen gas itself is an excellent coolant, and could be used to cool the blades. If oxygen is used instead of air then efficiencies greater than 60 percent have been predicted⁽⁵³⁾ for aphodid burners. In the near term, however, it is not likely that oxygen will be used in the combustion, and for Table 6.8 a range of 40 to 50 percent has been selected for possible IUS applications.

TABLE 6.8. TECHNICAL CHARACTERISTICS OF ALTERNATIVES
CONVERSION SUBSYSTEM TECHNIQUES

Conversion Subsystem Technique	Energy Efficiency, %		Power Storage Density, kW/m ³		Estimated Life, Years	
	High	Low	High	Low	High	Low
Fuel Cell	65	50	0.79	0.59	≥ 7	5
Gas Turbine	50	40	Unknown	(0.57)	≥ 20	≤ 10

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The power densities, expressed in kW/m^3 (kW/ft^3), for a fuel cell subsystem shown in Table 6.8 are based upon data related to the Pratt and Whitney Aircraft FCG-1 Program, and reflect projected values. Early installations are likely to have a power density of about 21 kW/m^3 (0.59 kW/ft^3) while later installations may achieve a value of about 28 kW/m^3 (0.79 kW/ft^3). Until large fuel cell or gas turbine subsystems are built power density estimates can only be tentative. For this reason only a rough estimate of 20 kW/m^3 (0.57 kW/ft^3) has been assigned to the gas turbine.

Gas turbines may best operate efficiently for relatively short times under full load, e.g., a peaking application. In order to minimize thermal cycling, and thus promote longer life, gas turbines may have to be kept under a small load, or under essentially no load, but with enough heat being generated to maintain the energy converter at temperature. This type of operation, if found necessary, would be similar to a "spinning reserve" capability. Lifetimes in excess of 20 years might then be expected for developed units, maintained on a periodic basis. The initial turbines produced, however, may only have a life of about half this value, as Table 6.8 shows, until all problems identified during operation are resolved.

Fuel cells are flexible in their mode of operation, and operate efficiently over a broad range (25 to 125 percent) of the nominal power rating. The duty cycle restrictions are therefore minimal, nevertheless, life data are not available for energy storage applications, particularly with hydrogen as fuel. A life of 40,000 hours has been predicted for a similar type of "reformer" fuel cell, hence the estimated range for fuel cell life is given as 5 to 7 years, depending on the number of hours of operation per year.

Cost Characteristics. Similar to the previous subsection on technical characteristics, the major subsystem costs will be treated separately. Published data have been used wherever possible. Just as with

electrochemical energy storage systems, trade-offs between performance and cost will be necessary when subsystems are specified. However, for the present purposes best estimates have been given for the type of duty cycle and capacity envisaged.

Production Subsystem. Capital cost estimates for the electrolyzer have been obtained from the literature and from several manufacturers. The data are shown in Table 6.5. Some caution is suggested for the values, since there appears to be some sensitivity to design operating conditions (i.e., voltage, current density, temperature, and pressure). Electrolyzer capital costs have been escalating steadily to present day levels ranging over 100-150 \$/kW (hydrogen equivalent produced). Inclusion of auxiliary equipment, shipping, insurance, and installation can easily drive the cost beyond 300 \$/kW [or about 9900 \$/kg (4500 \$/lb) of hydrogen].

As indicated in Table 6.9, about 20 percent of the installed cost constitutes delivery and installation. Of the remaining 260 \$/kW about 40 \$/kW covers power conditioning equipment^(49,54,55). That leaves 220 \$/kW for the electrolyzer and auxiliary equipment (e.g., stills, deoxygenator for the hydrogen and dryers).

Manufacturer's information suggests a start-up cost of 25 \$/kW, and literature data indicate 2 mills/kWh for O&M. Salvage value is taken to be 25 \$/kW for the common electrode materials (e.g., iron, nickel, cobalt). This could be easily exceeded for noble metal electrode/electrode catalysts being considered for high performance electrolyzers.

Storage Subsystem. Various literature sources have reported cost estimates for compressed gas storage.

- 9-12 \$/kWh for 6.9 MPa (1000 psig) storage at a 50 percent round trip efficiency⁽⁴⁹⁾
- 8-12 \$/kWh (4-6 for commercial pressure bottles, 4-6 for compressors) for hydrogen and oxygen storage^(5,38).

TABLE 6.9. COST CHARACTERISTICS OF A PRODUCTION SUBSYSTEM

Subsystem Type	Capital Cost (Electrolyzers) \$/kW	Installation Cost, \$/kW	Start-Up Cost, \$/kW	O&M Cost, \$/kWh	Salvage Value, \$/kW
Water Electrolysis	150-270	60	25	0.002	25

Notes: (1) Costs based on the hydrogen equivalent delivered to storage.
 (2) Low temperature, commercially available electrolyzers used as basis for O&M cost.

- 34 \$/kWh for 13.8 to 17.2 MPa (2000-2500 psig) storage⁽²⁹⁾
- 10-34 \$/kWh⁽⁵⁰⁾.

The last range of values, which was also based on BCL analysis, is listed in Table 6.10. The higher value represents current technology.

For installation, about 10 percent of storage capital costs should be appropriate for hydrogen storage (about twice that if both hydrogen and oxygen are stored). O&M is estimated to be roughly 3 mills/kWh. Salvage should be nominally 5 \$/kW.

For hydride storage, here, too, various costs have been estimated in the literature.

- 14-70 \$/kWh capital cost for an iron-titanium alloy subsystems⁽⁵¹⁾ for 1-5-hr discharge periods.
- 16 \$/kWh for a similar hydride storage in a 26 MW, 260 MWh installation⁽²⁹⁾.

In Table 6.10 a range of 16-50 \$/kWh for less than 10-hr discharge has been selected.

Installation costs for hydride storage are expected to range 60-100 \$/kW over the near term. Start-up costs depends on the activation procedure used to condition the material for hydrogen absorption/desorption. A material is available that removes the necessity for activation⁽⁵⁶⁾; however, its present cost is about 3 to 4 times the goal of 1.10 \$/kg (0.50 \$/lb). O&M costs are suggested to be 3 mills/kWh⁽⁵⁵⁾. A salvage value of 80 \$/kW is assumed on the basis of recovery of the iron-titanium alloy at present day cost.

Conversion Subsystems. Conversion subsystem costs are summarized in Table 6.11.

Current conventional fuel gas turbines cost 100-135 \$/kW. Hydrogen-fueled machines operating at higher turbine inlet temperatures should cost at least

TABLE 6.10. COST CHARACTERISTICS OF ALTERNATIVE STORAGE SUBSYSTEM TECHNIQUES

Storage Subsystem Technique	Capital Cost, \$/kWh		Installation Cost, \$/kW		Start-Up Cost, \$/kW	O&M Cost, \$/kWh	Salvage Value, \$/kW
	High	Low	High	Low			
Compressed Gas Storage (Mechanical) (a)	34	10	60	30	10	0.003	5
Metal Hydride Storage (Chemical) (b)	50	16	100	60	50	0.003	80

(a) Storage pressures assumed in the range of 1000-2000 psi.

(b) Iron-titanium alloy assumed.

TABLE 6.11. COST CHARACTERISTICS OF ALTERNATIVE CONVERSION SUBSYSTEM TECHNIQUES

Conversion Subsystem Technique	Power Related Capital Cost, (a) \$/kW		Installation Cost, \$/kW	Start-Up Cost, \$/kW	O&M Cost, \$/kWh	Salvage Value, (b) \$/kW
	High	Low				
Fuel Cell	390	190	60	25	0.002	85
Gas Turbine	135	100	<60	<25	0.005	?

(a) Includes costs of auxiliary equipment such as heat exchangers, controls, reformers where necessary, but not cost of power conditioning equipment.

(b) Salvage value based upon anticipated materials costs for initial installations.

the higher value. Experience with conventional machines suggests installation costs of about 60 \$/kW, and start-up costs less than 25 \$/kW. O&M are taken to be 5 mills/kWh based on escalation of a reported 1.9 mills/kWh⁽⁵⁵⁾ and allowance for higher maintenance costs. Salvage can be taken as no value, a practice adopted by some utilities for peaking gas turbines.

For fuel cells, again, the literature contains wide ranges of costs

- 200 \$/kW for hydrogen-oxygen fuel cell^(46,48)
- 140-290 \$/kW⁽⁵⁵⁾
- 150-300 \$/kW⁽⁵⁷⁾
- 350 \$/kW has been estimated by the Synthetic Fuels Panel capable of 16,000-hr operation.
- 150 \$/kW goal for Pratt & Whitney Aircraft's FCG-1 reformable fuel cell in mass production quantities--not likely to be met⁽⁵⁸⁾
- 175 \$/kW in the long term^(49,51).

In Table 6.11, a long-term estimate of 190 \$/kW has been adopted and 390 \$/kW for near-term fuel cells (including heat exchangers, controls, and related equipment).

Installation costs are reported to be about 60 \$/kW⁽⁴⁶⁾. Start-up should be similar to that for electrolyzers. O&M has been estimated to be 2 mills/kWh based on escalation of the literature value of 1.5 mills/kWh^(48,55,59). Salvage is estimated at 85 \$/kW based on recovery of noble metal from the electrodes, which represent one-fourth of total fuel cell costs⁽⁴⁹⁾.

Net Replacement Costs. Data for projected life of the subsystems have been combined with capital cost estimates to derive replacement costs shown in Table 6.12. For the storage subsystem, an average discharge time of 6 hr has been assumed based upon data given in Table 6.13. Installation costs and salvage value have not been included.

Beyond 1995, decreases in capital cost will be relatively small unless a breakthrough in material technology occurs. However, a continuing improvement in both performance and life can be expected.

TABLE 6.12. ESTIMATED SUBSYSTEM REPLACEMENT CAPITAL COST/TIME SCHEDULE

Subsystem Alternative	Years After Installation																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Water Electrolyze	270										170										150
Compressed Gas Storage	204					105															60
Metal Hydride Storage	300			255										108							
Fuel Cell	390					280					230							195			
Gas Turbine	135					120					110										100
Power Conditioning	80																				

Notes: 1975 is assumed to be the installation date of the original subsystem equipment. The power conditioning equipment is expected to have a life of 20 years or more. Costs given as \$/kW in 1975 dollars. Does not include installation costs. Average discharge duration assumed to be 6 hours. Salvage values not included.

TABLE 6.13. SUMMARY OF ESTIMATED TOTAL ENERGY STORAGE SYSTEM CAPITAL COSTS
FOR VARIOUS SYSTEM CONCEPTS

TUS Application	Number of Generators Installed	System Concept (a)	Installed E/S Capacity (b) kWh	Available Capacity kWh	Discharge Time hr	Power Conditioning Subsystem Cost, \$/kW	Production, Storage(c) and Conversion Subsystem Cost \$/kW	Installation and Start-Up Cost \$/kW	Total E/S System Capital Cost(d) \$/kW
(1) <u>1000-Unit Apartment</u>	5	A	1,494	1,056	4	80	796	240	1,116
	4		5,750	4,065	7	80	876	240	1,196
	5	B	1,494	1,056	4	80	860	320	1,260
	4		5,750	4,065	7	80	978	320	1,378
(2) <u>Village Complex</u>	7	A	4,497	3,179	2	80	712	240	1,032
	6		47,579	33,638	11	80	870	240	1,190
	7	B	4,497	3,179	2	80	737	320	1,137
	6		47,579	33,638	11	80	969	320	1,369

(a) Subsystem identified in Table 6.4.

(b) A 50 percent round trip efficiency assumed.

(c) Based upon installed capacity.

(d) Initial installed capital cost based upon 1975 cost estimates for delivered capacity.

Total Energy Storage Concept Costs. Cost data for the candidate chemical energy storage concepts are assembled in Table 6.13. An optimistic round trip efficiency of 50 percent has been assumed in calculating the installed capacity requirements for several IUS scenarios implemented in 1975 (see also the discussion in Volume II). Overall efficiencies are summarized in Table 6.14. As expected, short discharge time and small capacity result in low capital costs (Table 6.13). Comparison with results from Section 5 on electrochemical energy storage indicates that chemical energy storage would be less efficient and at least twice as expensive.

If installation is deferred until 1985 and cost reductions indicated in Table 6.12 are realized, a 30-35 percent reduction in total capital costs could result, as shown in Table 6.15. Note that Concept A, using compressed gas storage, offers a potential for lower capital costs than Concept B, which uses metal hydride storage. A further reduction could be attained if a reversible water electrolyzer⁽⁴⁶⁾ or reversible fuel cell⁽⁵⁴⁾ was used to combine the production/conversion functions into one device. In that case a modified Concept A might cost 947 \$/kW in 1975, or 534 \$/kW if deferred to 1985 (assumptions include round trip efficiency of 50 percent, installation/start-up cost of 180 \$/kW, 7-hr discharge and reversible device costs of 400 \$/kW in 1975, and 150 \$/kW in 1985).

Research and Development Opportunities

As a consequence of a review and analysis of state of the art and advanced technology, as well as attendant economics, related to chemical energy storage, it has been concluded that the most viable candidate concept for near-term application to an IUS installation would be Concept B. The potential is high for Concept D farther in the future. It is appropriate to conclude this section by addressing the R&D needed to achieve practical commercial implementation.

TABLE 6.14. ESTIMATED OVERALL ENERGY STORAGE SYSTEM ROUND-TRIP EFFICIENCIES FOR VARIOUS SYSTEM CONCEPTS

Candidate System Concept (a)	Estimation Limit	Subsystem Efficiency Contributions (b)	System Round-Trip Efficiency, Percent
A.	High	90 x 98 x 65 x 95	55
	Low	77 x 75 x 50 x 90	26
B	High	90 x 95 x 65 x 95	53
	Low	77 x 75 x 50 x 90	26
C	High	90 x 98 x 50 x 95	42
	Low	77 x 75 x 40 x 90	21
D	High	90 x 95 x 50 x 95	41
	Low	77 x 75 x 40 x 90	21

(a) System concept identified in Table 6.4.

(b) Subsystem efficiency values listed in the following order; production, storage, conversion, and power conditioning.

TABLE 6.15. EFFECT OF IMPLEMENTATION TIME FRAME ON CAPITAL COST OF CHEMICAL ENERGY STORAGE

Candidate System Concept	Implementation Time	Installed Cost, \$/kW ^(a)			
		1000-Unit Apartment		Village Complex	
		5 generators	4 generators	7 generators	6 generators
A	Immediate (1975)	1,172	1,317	1,076	1,509
	Near term (1985)	791	844	755	915
B	Immediate (1975)	1,343	1,555	1,201	1,838
	Near Term (1985)	922	1,013	861	1,135

(a) Values are 1975 dollars. Immediate (1975) time frame data from Table 6.13.

A review of ongoing programs in water electrolysis reveals that activities aimed at obtaining major performance improvements are concerned with achieving higher operating temperature and pressure and increased electrode surface area and catalytic activity. At the present time the performance limitation imposed by the oxygen electrode should receive the most emphasis. The scheduling of achievement places hope for attaining 80 percent energy (thermal) efficiency by 1980, 90 percent by 1985, and near 100 percent by 1990.

With regard to compressed gas storage for Concept B, there is a need for high strength materials that are not susceptible to hydrogen embrittlement and yet amenable to low cost fabrication and inspection methods. Composite materials used in a winding fabrication technique merit consideration. The merits of a regenerative compressor for an IUS energy storage duty cycle should also be investigated.

The use of metal hydride storage for Concept D awaits further development beyond laboratory-scale experimentation in order to accumulate operational and component life data. Other studies should be conducted to determine the most efficient hydride bed heat transfer concept. Here again container materials are needed, not only to resist hydrogen embrittlement, but reactant corrosiveness and fatigue caused by thermomechanical cycling. The economic processing of hydride-forming metals and their long-term stability to contaminants (e.g., oxygen, nitrogen, and water vapor; also, oil from hydrogen compressors) also warrants attention.

The principal problems associated with fuel cell applications are still the extension of service life and reduction of cost, and both are related to the amount of noble metal electrode/electrocatalyst used in a cell. Erosion problems caused by gas evolution at the electrodes of cells capable of reversible operation suggest the desirability of abandoning particulate catalysts in favor of solid electrodes.

Alkaline electrolytes indicate promise of reducing corrosion problems and, therefore, increasing cell life. They also offer the opportunity for developing nonnoble metal electrodes/electrocatalysts (e.g., Raney nickel). However, they do introduce a potential problem of cell performance reduction because of carbonation, which can be alleviated by CO₂ scrubbers or by careful sealing and minimal use of organic-based materials.

Although increasing operating temperatures can improve cell performance (and may obviate the need for expensive electrode catalysts), there is an accompanying increase in the severity of corrosion and sealing problems. The water vapor partial pressure is also increased as is the chance for the occurrence of a "vapor-polarization" effect; increased operating pressure can, however, provide compensation to inhibit this behavior. It is clearly desirable to have the cells designed for the higher pressure/temperature regime without a disproportionate increase in materials and fabrication costs. Finally, as with other subsystems, considerable development effort will be needed to scale up an acceptable design and to obtain substantial operational data. Beyond that, fabrication techniques will have to be adapted for mass production in quantities sufficient to meet IUS application demand.

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7. COMPRESSED AIR ENERGY STORAGE

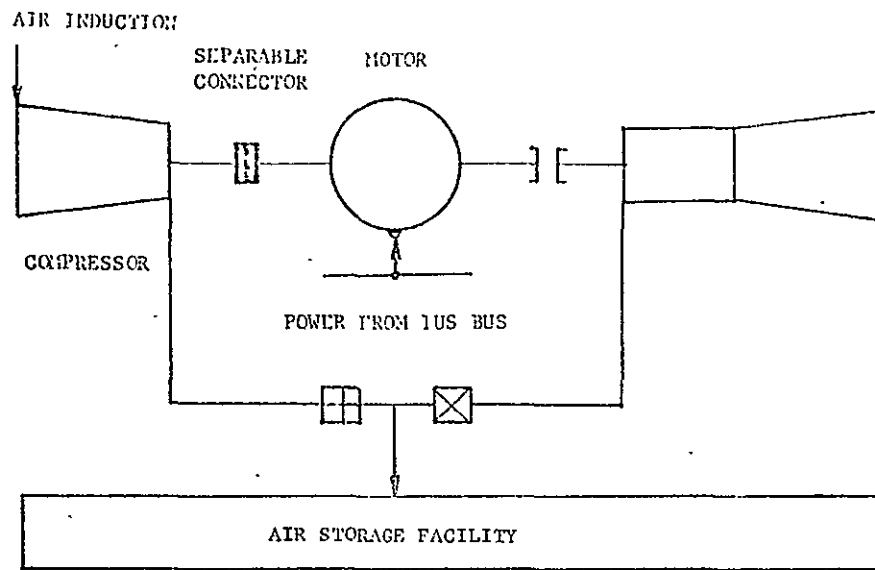
Basic Aspects of Compressed Air Energy Storage*

Compressed air energy storage is generally visualized as a functional modification of the open-cycle combustion gas turbine, a prime mover whose popularity for such applications as utility peak shaving stems from a combination of low first cost and quick-start capability. The modification is logically derived from the fact that a disproportionate allocation of expansion turbine shaft power is used for compressor operation rather than for external application. If this feature of the gas turbine could be circumvented, then practically all of the turbine shaft power could be dedicated to turning an electrical generator. One method of realizing this change would be to separate the compression operation from the remainder of the gas turbine cycle. That is, compressed air could be stored in sufficient quantity to later operate the hot gas generator (combustion chamber and turbine) over a desired discharge period. Variations on this basic approach can be devised by altering the energy management during the various thermodynamic processes of the cycle.

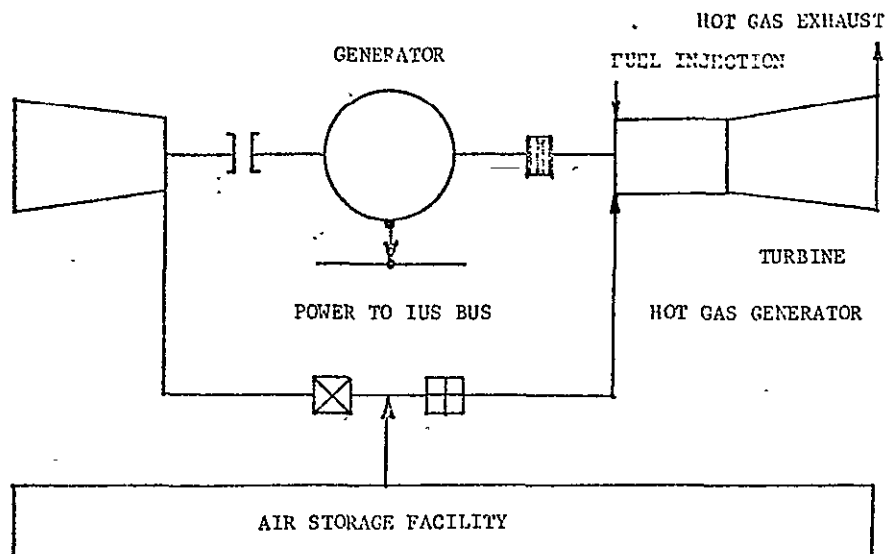
The operational essentials of the compressed air energy storage technique can be described with the aid of Figure 7.1. In Figure 7.1 (A), the machinery is set up for the charging mode. That is,

- The synchronous machine (operating in a motor mode) is coupled to the compressor but not to the turbine.
- When the motor is started and is drawing power from the IUS power grid, the compressor is motor driven to charge the air storage facility. Ideally, the charging process would be adiabatic.

* Much of the material in this subsection is based upon Battelle contributions to Volume II of Reference 1.



(A) CHARGING MODE



(B) DISCHARGING MODE

FIGURE 7.1. MACHINERY ARRANGEMENTS FOR OPERATION
OF COMPRESSED AIR ENERGY STORAGE SYSTEM

- Upon completion of the charging process the storage facility would be placed on standby with the isolation valves closed and the motor disconnected (mechanically from the compressor and electrically from the power grid). Also ideally, the storage process would be adiabatic during the holding time period.

In Figure 7.1 (B), the machinery is arranged to illustrate the discharge mode. That is,

- The synchronous machine (operating in a generator role) is coupled to the turbine.
- When the discharge valve is opened, air is allowed to reach the turbine for a "windmill" start.
- The combustion chamber is fired, and the turbine is accelerated to synchronous speed with appropriate controls.
- The generator is connected to the IUS power grid, and power generation can be continued until the usable air mass in the storage facility has been depleted.

Several important observations can be keyed to the schematics of Figure 7.1. First, the split in the conventional gas turbine cycle operation by the intervening air storage operation obviates the necessity for the careful compressor/turbine matching required in the conventional machine. Second, if available charge time exceeds the discharge time, the high mass flow capability of the axial flow compressor is no longer a necessary and restrictive requirement. Third, the "blowdown" discharge operation for useful power generation readily identifies the critical design/operating variables as (1) air mass storage capacity, (2) airflow rate handling capability, and (3) energy addition by heating. Mass storage and flow rate together govern the duration of power generation; whereas, flow rate and energy addition determine the power level available.

Yet another important feature to be noted in Figure 7.1 is the pivotal nature of the compressed air storage facility, which is depicted as a closed vessel accessible from the compressor or to the hot gas generator

only through the piping and valves shown. The design variables for the storage facility are intuitively obvious, viz, (1) the material nature of the storage vessel, (2) the elevation of the vessel referenced to ground surface, (3) the pressure, temperature, and heat transfer capability (note that heat and mass removal/leakage from the stored air constitute system-chargeable losses), and (4) method of discharge flow control to produce desired conditions at the entrance to the hot gas generator. The first two variables suggest options for man-made or naturally occurring reservoirs; the third variable is keyed to the first two, and the fourth depends upon the characteristics of the discharge valving arrangement.

In closing this introductory subsection, it is worth noting that a considerable literature inventory has been built up in recent years, and, as mentioned in Section 2, the potential for premium fuel conservation has accelerated study of the compressed air energy storage alternative. References 1-49 provide ready access to this information base.

Alternative Approaches for Implementation

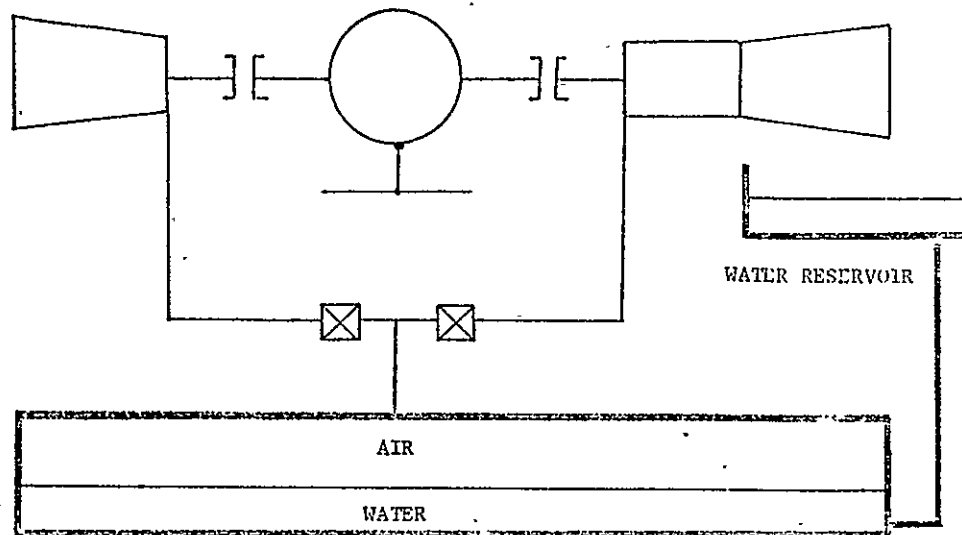
Without further elaboration, the basic gas turbine cycle represented in Figure 7.1 could be readily modified into a variety of cycle alternatives.

- Split simple cycle
 - Basic split-cycle
 - Compressor interstage and/or after cooling incorporated
 - Regenerative fuel vaporization added
 - Regenerative air preheating added
 - Turbine (interstage) reheat incorporated
 - Thermal energy storage substituted for heat rejection to expendable cooling water used in compressor interstage/after cooling
- Combined cycle (split gas turbine and complementary steam turbine).

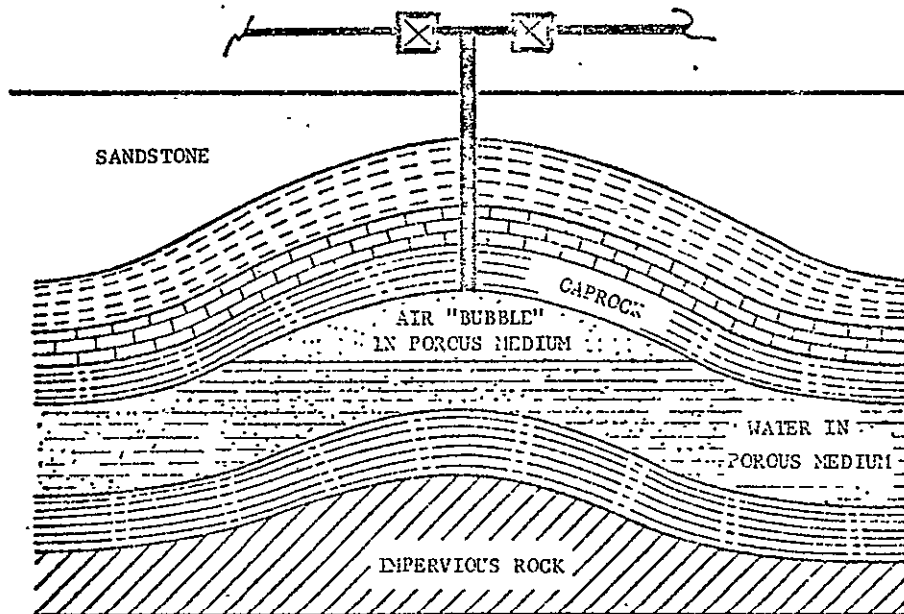
Not only are there alternatives possible with the basic thermodynamic cycle, there are also many more choices available in the major subsystems, i.e., air compressor, air storage facility, and air heating. Air compressor alternatives include: (1) axial flow, (2) axial flow with centrifugal boost, (3) centrifugal, and (4) reciprocating. Air storage facility alternatives can be classified as including: (1) fabricated pressure vessel and (2) geological-mass integral reservoir (both artificially created and naturally occurring reservoirs). Artificially created reservoirs are associated with the intentional removal of geological material for commercial recovery and/or air storage, and they include hard rock excavations, solution-mined cavities, depleted oil/gas reservoirs, and abandoned mines. Naturally occurring reservoirs include caves and aquifers.

Another multiplication of alternatives for the air storage facility arises in connection with the fluid mechanics during discharge. A constant volume storage facility exhibits pressure decay in proportion to rate of mass withdrawal during discharge. This behavior would necessitate a rather complex valving arrangement to provide simultaneous control of mass flow and pressure level at the entrance to the hot gas generator. It may also happen that the peak-to-peak pressure variation for the full duty cycle might be unnecessarily or undesirably high and could lead to wall material fatigue. A method of achieving constant pressure operation by hydrostatic compensation is illustrated in Figure 7.2. In Figure 7.2 (A), a bulk water reservoir is used, and in Figure 7.2 (B) the natural compensation from an aquifer is employed. Note that in the former, selection of differential height between the water reservoir and air storage facility governs the pressure level of the stored air. In the latter, the storage pressure level is set by the inherent pressure of the aquifer.

Alternatives to air heating can be divided into: (1) no fuel addition, (2) conventional constant pressure combustion of different fuels in various burner configurations, and (3) unconventional heating techniques (e.g., fluidized-bed combustion). The "no fuel" case has been studied in Reference 41, which points out the necessity for using thermal energy storage of the heat of compression.



(A) BULK WATER RESERVOIR TECHNIQUE



(B) AQUIFER TECHNIQUE

FIGURE 7.2. METHODS OF HYDROSTATIC COMPENSATION OF AIR STORAGE FACILITY TO ACHIEVE CONSTANT PRESSURE OPERATION

The discussion in this subsection is concluded with some remarks regarding suitable site availability. There is a distinct difference in the site requirements for dispersed electric utility substations and an IUS application. A site location for a utility substation remote (up to say 50 miles) from the load center could be tolerated (depending upon electrical transmission costs); but, in an IUS installation, the compressed air energy storage machinery must be housed with or near the baseload generating equipment. Since extensive pneumatic transmission lines would be prohibitively expensive, the air storage facility (if it is integral with a geological mass) must be located essentially beneath the IUS load complex (apartment or village). Although a paper reconnaissance of geology conducted during the study reported in Reference 1 suggested that suitable sites should be available near many utility load centers, this observation is much too coarse to be applied directly to the IUS. Therefore, it is concluded that underground compressed air storage application to IUS would be site limited (especially in the case of the apartment complex).

Evaluation of Selected Candidate Compressed Air Energy Storage Concepts for IUS Application

Selection of Candidate Concepts

In the previous subsection, it was suggested that numerous alternative implementations could be postulated for: (1) thermodynamic cycle details, (2) air compressor designs, (3) air storage facility arrangements (both configuration and pressure control), and (4) air heating devices/fuels. Obviously, the number of possible combinations is unwieldy. However, based upon experience in support of the work reported in Reference 1, three concepts, each having distinctive features, have been selected for preliminary evaluation and are identified in Table 7.1. The IUS requirements to which they must be matched are summarized in Table 7.2.

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TABLE 7.1. IDENTIFICATION OF CANDIDATE COMPRESSED AIR ENERGY STORAGE
CONCEPTS FOR IUS APPLICATION

Candidate Concept	Cycle	Air Compressor	Air Storage Facility	Hot Gas Generator	Fuel
A	Split simple cycle gas turbine	Axial flow with centrifugal boost and aftercooling	Fabricated steel casings with hydraulic compensation	Conventional	No. 2 Distillate oil
B	Split simple cycle gas turbine	Axial flow with centrifugal boost and aftercooling	Hard rock (granite) excavated cavity; uncompensated	Conventional	No. 2 Distillate oil
C	Split simple cycle gas turbine	Axial flow with centrifugal boost. No aftercooling	Hard rock (granite) excavated cavity uncompensated plus thermal storage cavity filled with ceramic elements	No burner	None

TABLE 7.2. POWER/ENERGY REQUIREMENTS FOR COMPRESSED AIR ENERGY
STORAGE APPLICATION TO IUS SCENARIOS

IUS Application	No. of Baseload Generation Units	Peak Power Output Required From Storage, MW	Energy Storage Required, MWh
1000-Unit Apart- ment Complex	5	0.4	1.3
	4	0.9	4.9
Village Complex	7	2.9	3.8
	6	7.7	40.

Candidate Concept A. Because fabricated pressure tanks in large sizes (volume) are very expensive (about \$5000 for a 5.7 m^3 (200 ft^3)) vessel rated at 13.8 MPa (2000 psi), a concept of using oil/gas-well casing described in Reference 33 appears to have considerable merit. As sketched in Figure 7.3 for an IUS installation, an array of holes would be drilled into the ground, cased and cemented. However, this string would be manifolded at the bottom as well as the top. Isolation valves could be provided for each string to enhance operational availability of the facility in the event of individual casing failure. The depth, casing diameter and number of holes would be cost-optimized to satisfy the volume requirements associated with the energy storage and the operating pressure level desired.*

Hydrostatic compensation has been chosen to allow constant pressure operation (about 213 m (700 ft) of hydraulic head, exclusive of line losses, would be required for a hot gas generator pressure ratio of 20), and thus minimize mechanical fatiguing of the casings.

The choice of hot gas generation parameters is quite conservative; cycle pressure ratio of 20 and turbine inlet temperature of 1144 degK (1600 degF). For convenience, the parametric results published in References 7 and 28 have been used for performance estimation in this study. For these conditions, a specific storage volume requirement of $0.28 \text{ m}^3/\text{kWh}$ ($10 \text{ ft}^3/\text{kWh}$) is indicated.

Candidate Concept B. In Concept B, the air storage facility becomes a cavity excavated from a suitable hard rock geological mass (say granite or dolomite) as sketched in Figure 7.4. Further, because site matching with a water reservoir may pose some difficulty, the idea of constant pressure operation (as in Concept A) has been sacrificed for constant volume operation (therefore, variable cavity pressure). Since constant supply pressure to the burner is still desirable to keep the hot gas generator operating near design point pressure ratio**, a trade-off has been made, namely, cost of a

* Note that this method is really a variant of the "line-packing" technique suggested for gas storage in Section 6.

** Turbine speed control is effected by fuel control, which, in turn, determines turbine inlet temperature.

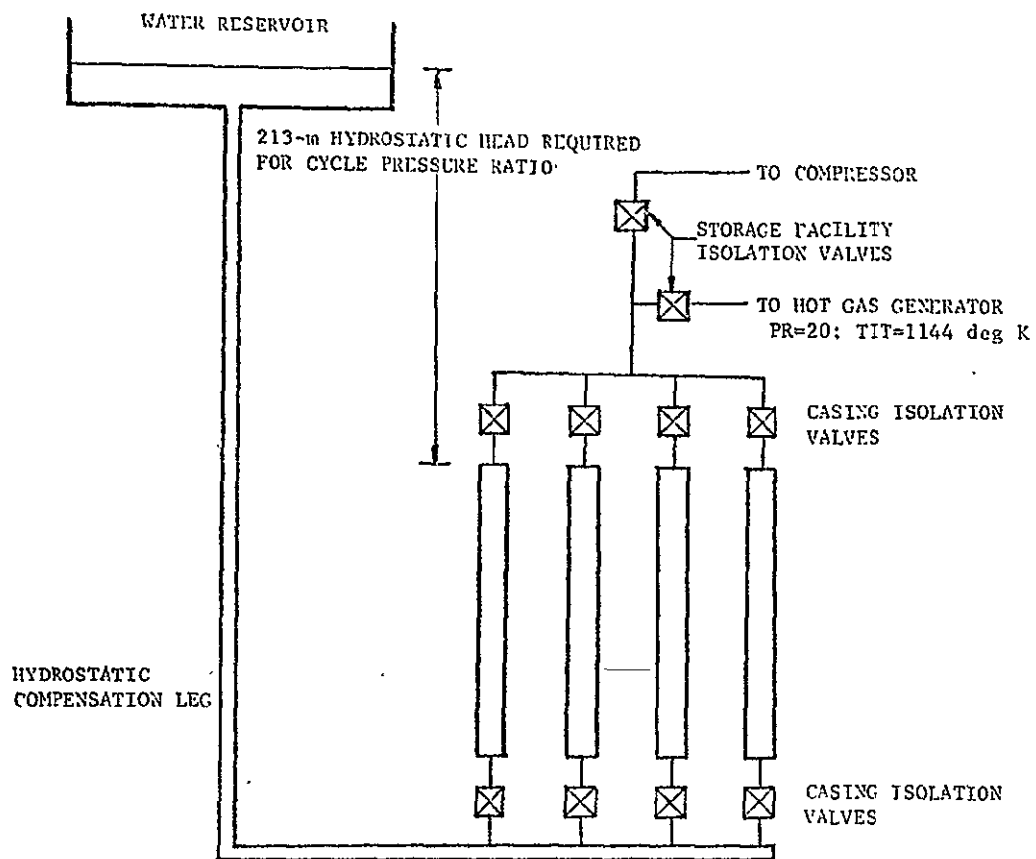


FIGURE 7.3. SCHEMATIC OF CANDIDATE CONCEPT A

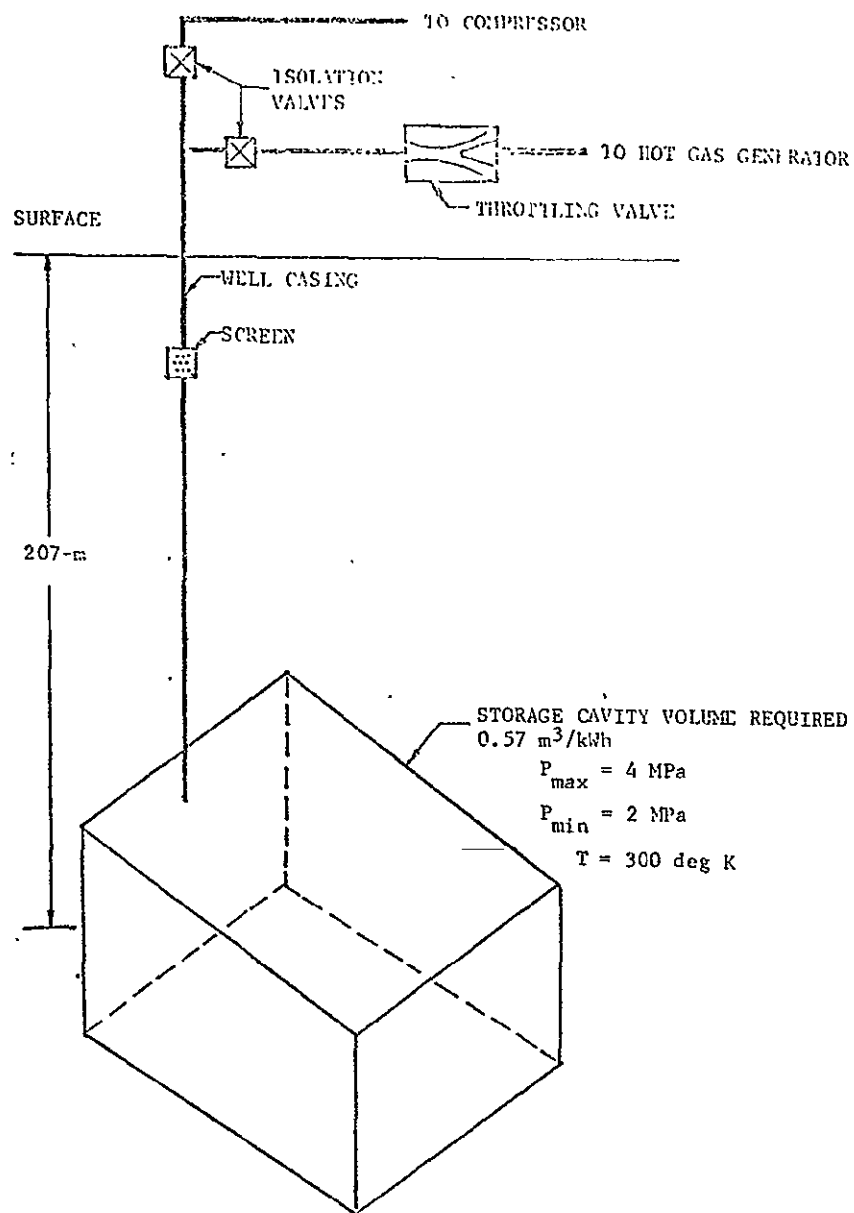


FIGURE 7.4. SCHEMATIC OF CANDIDATE CONCEPT B

hydraulic compensation reservoir and vertical shaft for a set of throttling valves and associated controls, as well as an increased compressor charging pressure capability.

The 20-to-1 pressure ratio of Concept A becomes the minimum for the cavity in Concept B. This can be obtained by locating the cavity at a depth of 207 m (680 ft) below surface in order to use the geostatic pressure gradient. Then the compressor must be capable of 40-to-1 pressure ratio to provide working air above the cushion gas. The remainder of the subsystem components are the same as for Candidate A.

Candidate Concept C. The issue of premium fuel conservation is addressed directly with Concept C in which power generation (i.e., discharge mode of operation) is accomplished without fuel burning. The basic subsystems adopted here are the same as for Concept B, with two major exceptions: (1) no combustion chamber and associated fuel supply/controls and (2) the insertion of a thermal storage cavity between the compressor and the main air storage cavity. (see Figure 7.5). This thermal storage cavity would contain suitable media such as a bed of refractory pebbles or perforated brick. The necessity for thermal storage to make this concept practical has been demonstrated on thermodynamic grounds in References 41 and 47.

Technical Characteristics of Candidate Concepts. Attention is focused on rendering a technical characterization of the three candidate concepts selected for the IUS application. This representation is made in terms of the following:

- System efficiency figure of merit
- Power/energy density
- Hardware availability
- Transportability
- Operational availability/reliability/maintainability
- Useful life
- Safety considerations

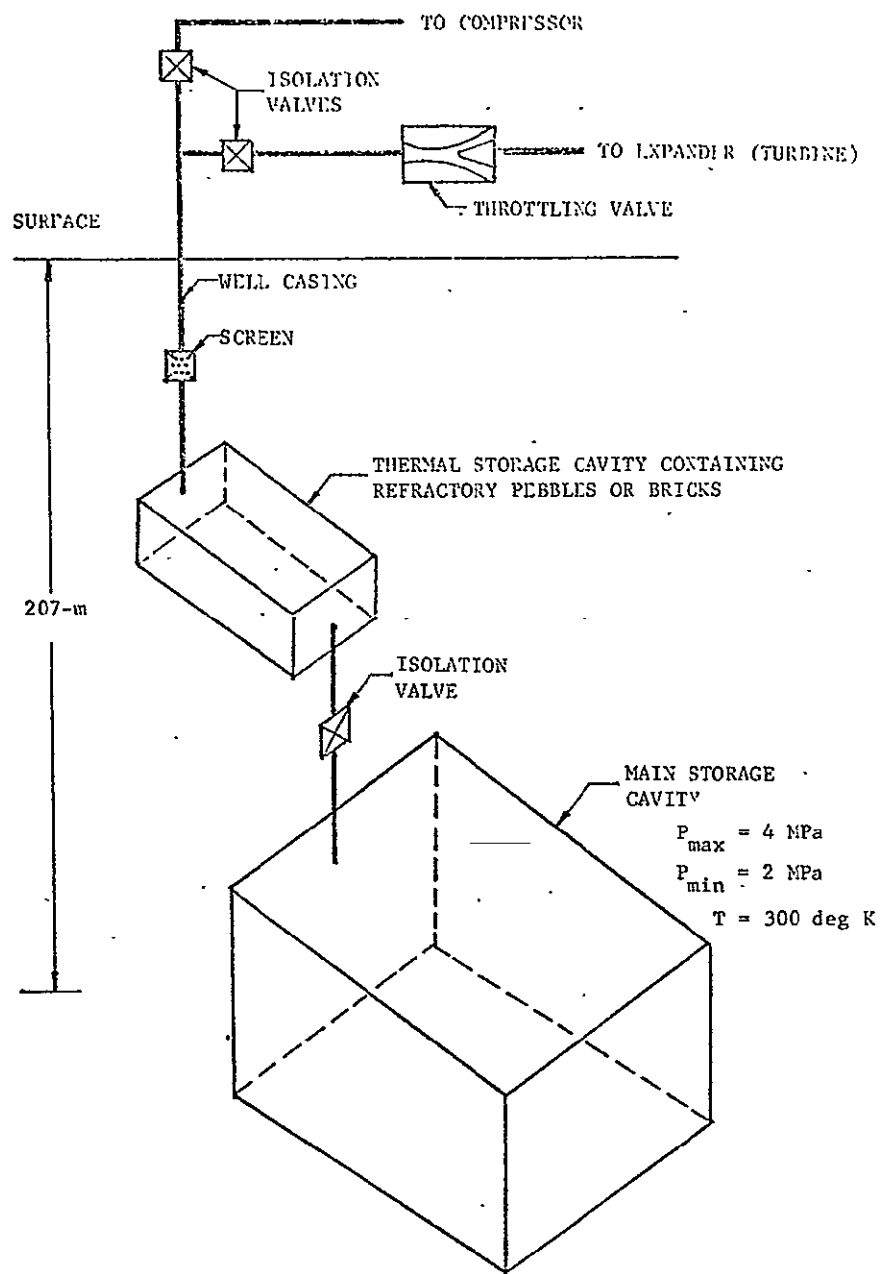


FIGURE 7.5. SCHEMATIC OF CANDIDATE CONCEPT C

- Expansion capability
- Environmental concern.

System Efficiency. Unlike the other energy storage technologies, compressed air energy storage that retains the hot gas generator feature of the gas turbine consumes fuel twice--once during charge (as base load generation fuel) and again during discharge (as burner fuel). The meaning of overall system efficiency, then, must be carefully considered. Here, the efficiency figure of merit used in Reference 1 is selected*; it is termed an "energy storage efficiency", η_{ES} , and is defined by

$$\eta_{ES} = \frac{\eta_{EC}}{\eta_{BL}},$$

where η_{EC} is the energy conversion efficiency of the compressed air energy storage installation and η_{BL} is the energy conversion efficiency of the base load generation equipment (here, the diesel electrics chosen for the IUS scenarios).

Now, η_{EC} and η_{BL} are defined by

$$\eta_{EC} = \frac{E_{OUT}}{E_{AS} + E_{SC/GT}}$$

and

$$\eta_{BL} = \frac{E_{OUT}}{E_{BL}},$$

where

E_{OUT} is the anticipated electrical energy capacity of the compressed air energy storage unit

E_{BL} is the fuel heat rate of the base load generation equipment (here taken as 10,239 Btu/kWh for the IUS diesel electrics)

E_{AS} represents the energy from the base load generation that is required by the compressor to inject air into the storage facility; it can be determined from

$$E_{AS} = E_{BL} / (\text{compressor thermal efficiency})$$

* Investigations have differed in the choice of methods for computing "efficiency" (e.g., see Reference 37 for an alternative suggestion).

$E_{SC/GT}$ is the fuel heat rate for the split cycle gas turbine (here optimistically estimated as 2750 Btu/kWh for the hot gas generator previously described, i.e., pressure ratio of 20 and turbine inlet temperature of 1144 degK (1600 degF)).

Assuming a compressor efficiency of 85 percent,

$$\eta_{ES} = \frac{E_{BL}}{E_{AS} + E_{SC/GT}} = \frac{10,239}{12,046 + 2750} = 0.69$$

for candidate Concepts A and B. This energy storage efficiency is comparable to the "round-trip efficiencies" used for the other technologies.

For the limiting no-fuel concept (Candidate C), $E_{SC/GT} = 0$ and the maximum energy storage efficiency becomes equal to the compressor efficiency (in this case 85 percent). Note that this is an optimistic approximation, because allowance has not been made for the real efficiencies of thermal energy storage and turbine expansion. To do that, it is convenient to rewrite the expression for η_{ES} as

$$\eta_{ES} = \frac{E_{BL}}{\frac{E_{BL}}{(\text{compressor thermal efficiency})(\text{thermal storage efficiency})} + \frac{E_{BL}}{(\text{turbine expansion efficiency})}}$$

which, for some heuristic choice of component efficiencies, becomes

$$\eta_{ES} = \frac{1}{\frac{1}{(0.85)(0.85)} + \frac{1}{(0.90)}} = 0.40$$

for candidate Concept C. The point being illustrated is that efficiency has been traded off for relief from burning premium fuel in a hot gas generator.

Charge/Hold/Discharge Characteristics. The charge/discharge characteristics of all three candidate concepts are basically related to adequate allowance for line losses (i.e., equivalent friction losses associated with flow

through casing, valves, fittings) in the pneumatic circuits. Line size will, of course, be determined by which ever mode (charge or discharge) has the highest mass flow rate (which, in turn, is governed by the lowest time available for the operation). Concept C posses an extra equivalent circuit pressure drop owing to the thermal storage medium. There is also the problem of the time varying characteristics of the air temperature during discharge that must be consider in the control of power generation.

As implied in previous discussions, Concept A can approximate full discharge (i.e., 100 percent depth of discharge) in that the water from the hydrostatic compensation shaft can be allowed to fill the air storage volume. In Concept B, the cavern can generally be discharged to the local geostatic pressure level (considerations of cavern integrity makes it inadvisable to cycle below this pressure); this could correspond to 100 percent discharge if the maximum pressure is high enough. The discharge depth of Concept C is similar to Concept B.

With regard to holding characteristics, the principal problems to be noted are mass leakage and heat losses. Concept C is the most vulnerable since it involves both the most storage volume in excavated rock and relatively high (approximately the adiabatic temperature of compression) temperature levels in the thermal storage cavity.

Power/Energy Density. For compressed air energy storage concepts, it is useful to identify both a power density and an energy density. Power density is defined here as the power generated per unit mass flow through the turbine; it can be expressed in kW/kg/sec (kW/lb/sec). Energy density represents the useful electrical energy extracted per unit of air storage volume; it can be expressed in kWh/m³ (kWh/ft³). According to these definitions, power density characterizes the performance of the hot gas generator subsystem, and energy density characterizes the size of the air storage facility. Note that the reciprocal of power density is the turbine specific flow rate and that the reciprocal of energy density is specific storage volume. The principal virtue of the density-type definition is

that it is performance evaluation oriented (determining what a given system can do); whereas, the specific flow rate or storage volume is design oriented (determining the system needed to produce a given performance level).

In general, the power level of a single unit conventional combustion gas turbine can also be achieved by the hot gas generator subsystem of a compressed air energy storage installation. For similarly sized turbines, the conventional gas turbine has only one-third to one-fourth the generating capability of the energy storage split cycle arrangement (recall that in the latter, turbine shaft power is totally dedicated to driving the generator). Thus, presently available individual units in the range of 0.8 - 100 MW would, in the split cycle scheme, be capable of say 2.4 - 300 MW generation. Compared to the peak power capability required of the energy storage concept in the selected IUS scenarios previously listed in Table 7.2, it is clear that single units adapted from existing technology should readily meet the demand.

For the candidate concepts using hot gas generation (Candidates A and B) conservatively designed (pressure ratio of 20, turbine inlet temperature of 1144 degK (1600 degF)), the power density is estimated to be 4.365×10^{-5} kW/kg/sec (1.984×10^{-5} kW/lb/sec). The energy density for Candidate A is 35 kWh/m³ (0.1 kWh/ft³).

In estimating the performance of the compressed air energy storage candidates it was assumed that air leakage and heat loss during the holding time interval were negligible. Air leakage does degrade overall system performance, because energy is required for air compression, while no useful turbine work is extracted from the lost air. Heat loss during holding is, of course, also system chargeable loss since the energy is not recovered for turbine expansion work.

Hardware Availability. The technology of compressed air energy storage is derived from the information/experience base of well established industries. No particularly difficult design/manufacturing problems are expected for the

associated equipment of candidate Concepts A, B, and C. There are, nevertheless, some interesting points to be noted.

For Concept A, it is worth reiterating from the description associated with Figure 7.3 that the use of mass-produced oil/gas-well casing for the storage vessel(s) is perhaps the most practical near-term approach.

The problem of availability of suitable geological conditions for the underground storage caverns used in Concepts B and C generically falls in the present category. In Reference 1, a paper reconnaissance indicated encouraging prospects for having suitable sites available near major load centers for electric utilities. The scale of observation for that study, however, is much too coarse for the present needs. What is required is highly localized geological information for potential IUS locations; this information is, in general, suspected to be lacking and will probably have to be compiled for individual IUS installations by the developer.

Transportability. No difficulties in transporting subsystem modules are anticipated, since there is a wealth of experience with peaking gas turbine installations and, for Concept A, casing oil/gas wells.

Operational Availability/Reliability/Maintainability. The operational availability, reliability, and maintainability of the compressed air energy storage concepts could differ appreciably from that of the conventional gas turbine, primarily because of the increased number of subsystems and components. At the subsystem and component level, some similarities can be expected to experience with existing equipment (e.g., compressors, combustion chambers, and turbines). The least known subsystem would be the air storage facility, because there is no relevant prior experience for the daily duty cycles.

One of the problems that will affect availability/reliability/maintainability, as well as service life, is corrosion. Corrosion protection of in-ground structures (e.g., well casings) can be effected in several ways; but, the

most positive approach would be to provide cathodic protection (in either galvanic or electrolytic mode) in conjunction with a coating.

Another form of corrosion, "hot corrosion", can occur from salt contamination of the air supply (either because of a marine environment or the presence of salt deposits in an excavated storage facility) along with the presence of sulfur or vanadium in the fuel. Since the formation and condensation of sulfur or vanadium sulfates on hot turbine parts can lead to catastrophic corrosion, it is important to have adequate quality control of these contaminants (e.g., by having a fuel washing facility). The relatively low turbine inlet temperature assumed for Concepts A and B makes avoidance of condensation difficult. Concept C, of course, does not have this hot corrosion problem.

Useful Life. In Concept A, major subsystems are replaceable as modules with the exception of the hydrostatic compensation portion of the storage system. In Concepts B and C, the storage cavities are not replaceable in a modular sense. Lacking precedence, it appears reasonable to adopt the service life cited in Reference 1, namely, 20-25 years.

Safety Considerations. In addition to the hazard sources normally associated with a conventional peaking gas turbine and even the base load diesel-electric sets (viz, electrical equipment, rotating machinery, fuel storage, and high temperature components), there are additional hazards posed by large quantities of high pressure gas. Thus, not only are the IUS operational and maintenance crew exposed but also the general public beyond the immediate bounds of the IUS station. Certainly it would appear imperative to conduct a thorough systems safety analysis.

Among some of the readily identifiable potential hazards are:

- Rapid sequential occurrence of seismic-induced or cyclic-pressure-induced cavern failure, surface subsidence, and fuel tank damage

- Potential for fire/explosion arising from the injection of lubricant by the compressor into the storage facility components (Concept C is probably most vulnerable to serious consequences because of the thermal storage component).

Expansion Capability. The modularity of the major subsystems in a compressed air energy storage installation allows system expansion with relative ease. In the case of Concept A, even the storage facility can be expanding by installing another string of casing (the manifolding for hydrostatic compensation might pose some difficulty). In the cases of Concepts B and C (applicable to A, also) energy storage capacity increases would probably be easiest to achieve by increasing storage pressure levels (assuming that unused compressor capability is available).

Environmental Concerns. The environmental concerns that are related to the implementation of a compressed air energy storage concept include

- Acceptable land use policy (including aesthetics)
- Water quality assurance
- Air quality control
- Noise abatement.

Each of these concerns can be characterized in terms of regulatory activities and likely problems to be confronted in concept implementation.

Beyond local/regional planning and local zoning requirements, no uniform regulations exist that govern the suitability of surface land use for compressed air installations. It can be assumed that the aesthetics of the above ground equipment can be readily satisfied by the same approach used for the base load generation equipment or by acceptably configured modular enclosures. With regard to the subsurface air storage facility, the principal concerns would be the rather stringent assurance of ground control (i.e., avoidance of surface subsidence) and clear title to mineral rights. The underground facility would have to remain within the boundaries of the surface property unless legal arrangements could be made with adjoining

property owners. Note that of the three candidate concepts under scrutiny, Concept A may have greater difficulty than the others owing to the need for a water reservoir for hydrostatic compensation.

A requirement to avoid contamination of potable water supplies by drilling operations connected with test bores ("wells") and operational access bores will most likely be mandatory. Regulations governing well completion practices are quite compatible with the desirability of isolating the air storage facility to prevent leakage loss of stored air. This aspect is more of a problem for Concepts B and C than for A, which in reality comprises a group of cased wells connected in parallel.

Conventional gas turbine burner design practice is based upon providing locally stoichiometric combustion in the immediate vicinity of the fuel injectors downstream from which mixing with diluent air is promoted to obtain a desired exit temperature profile. Although concentrations of NO_x can be reduced by water injection into the combustion chamber to lower the flame temperature, such a measure should not be necessary in view of the low turbine inlet temperature postulated for this study. Obviously the no-fuel candidate Concept C is not beset with this kind of air quality control problem. However, particulate emission originating from the ceramic medium used in the thermal energy storage cavity could require screening/filtering.

A noise problem may occur for the machinery of all three candidate concepts--depending upon the exposure of people (IUS staff and nearby residents) to the noise, regulations governing such exposure, and the noise source(s) itself. Under the rules of the Occupational Safety and Health Act of 1970 (OSHA), maximum allowable occupational (therefore, of concern to IUS staff only) noise exposure levels are limited by a time-weighted standard covering continuous noise from 90 to 115 db.

- An exposure to continuous noise greater than 115 dbA for any length of time is prohibited.

An 8-hour (out of 24) exposure is the maximum continuous period allowed at 90 db and is decreased inversely with intensity (db) to 15 minutes at 115 db.

Concluding Remarks on Technical Characterization. Based upon the preceding survey of technical characteristics of the three candidate concepts of compressed air energy storage as applied to the IUS, several summary observations are advanced.

- There are no apparent technical barriers to devising split cycle compression/hot gas-generation equipment from existing combustion gas turbine technology. If combustion is to be retained, then multifuel capability must be incorporated in anticipation of shortages of various types and grades of fuels. This situation is inherent with Concepts A and B (Table 7.2). It is in this respect that Concept C offers an outstanding attribute of not requiring fuel beyond base load generation.
- Suitable geological conditions for underground air storage facilities may be wanting. It must be remembered that the IUS will be located where the load center (apartment complex or village complex) is sited in order to eliminate transmission and minimize distribution lengths. This prioritization means that compressed air energy storage, regardless of degree of application attractiveness, will be implemented only on an individual case basis dictated by site qualities.
- Modularization of major subsystems and components will provide the practical design flexibility desired.

Because of the limited scope of the present study, only one of the three candidates, namely, Concept B, is carried beyond the technical characterization

stage into the cost characterization. This decision is rationalized in the following manner. Concept A, as presently viewed, does not offer a clear cut technical superiority over Concept B, for which a better near-term prospect is supported by previously reported studies. It is suggested, however, that experience accrued with the NASA Ames Research Center installation of well casings for storage of the air supply for a blow-down wind tunnel⁽³³⁾ be monitored. Concept C is presently under study by two investigators^(41,47), and should also be monitored.

Cost Characterization of a Candidate Concept Selected for IUS Application.

In Reference 1, it is reported that wide ranges of cost estimates for compressed air energy storage have been found in the literature and that part of this scatter is attributable to the differences in aggregation of cost elements. Most investigators that cite cost breakdowns (other than the fixed/variable cost approach) do identify three basic categories: (1) power-related equipment costs, (2) energy-storage equipment costs, and (3) operation and maintenance costs. It is the identification of items (i.e., level of detail) for inclusion in each category that distinguishes the results of individual studies.

In this study, the information base and basic approach used in Reference 1 have been adopted to derive a cost characterization for candidate Concept B (Table 7.1). Considerations have been given to differences in power/energy scale and time frames of the source materials.

The power related costs for compressed air energy storage are identified here as comprising costs for: (1) compressor*, (2) hot gas generator, (3) electrical generator, (4) subsystem interfacing equipment (e.g., clutches), and (5) installation. Energy storage costs are lumped under air storage facility (i.e., storage cavity, access wells, well heads). Under operation and maintenance (O&M) costs, fuel cost has been separately identified in the customary fashion.

* A rigorous classification would place the compressor in the energy storage category, since, unlike the conventional gas turbine, the compressor does not participate in the power generation mode of the operational cycle.

Compressor costs were estimated from information presented in Reference 7, with adjustments for scale and time frame.

To derive a cost for the hot gas generator, a value (1975 dollars) of \$118/kW has been chosen to represent the cost of a conventional peaking gas turbine/synchronous generator set. This value is about equally divided between the gas turbine and the generator (i.e., \$59/kW for either assembly). Now the compressor represents about one-quarter of the gas turbine cost (judging from aircraft experience). Applying this reasoning here would lead to a hot gas generator cost of \$44/kW. As in Reference 1, this cost has been fixed for all design points studied (Table 7.2); that is, any cost sensitivity to power level (one order of magnitude spread) has been neglected.

With regard to interfacing equipment costs, the value of \$5/kW cited in Reference 1 (based upon utility experience) has been adopted here. This value is less likely to be optimistic than for the large scale applications contemplated in that study. Similarly, the installation cost of \$20/kW is also taken from Reference 1 (based upon utility experience with gas turbine installations).

The cost of an air storage facility will depend upon both physical characteristics (volume, geological setting) and construction techniques (civil engineering vs. mining methods). As pointed out in Reference 1, a data base for hard rock excavation costs is available from extensive experience. Reviewing the material in Reference 1 and taking into consideration the uncertainties attached to a conceptual as opposed to detailed site-specific design and associated construction technique, it is suggested that \$50/kWh is a fair estimate for Concept B.

A fuel cost estimate of 7.28 mills/kWh is based on \$0.36/gal of fuel, a heating value of 136,000 Btu/gal and the estimated hot gas generator heat rate of 2750 Btu/kWh. The balance of O&M costs of 10 mills/kWh is estimated from Reference 30 (after allowing for fuel costs).

The gross costs for compressed air energy storage Concept B implemented over the near term for the IUS scenarios of Table 7.2, is summarized in Table 7.3. These data do not, of course, include development costs, cost of money during construction, nor salvage. The net scenario cost, in life cycle terms, are treated in Volume II.

Opportunities for Research and Development

As is well known, the first commercial installation of a compressed air energy storage concept is scheduled for service inauguration in 1977 as an adjunct to a utility network in the Federal Republic of Germany^(32,34,48). The storage caverns for this facility are being created by solution-mining of a salt dome, and the above ground machinery design is being assembled from known technology.

Many investigators have identified topics for RDT&E to support the emergence of compressed air energy storage as a viable alternative for energy resource utilization. These topical areas generally fall in the category of storage facility or turbomachinery considerations. It is believed that for this study, the opportunities for R&D can be simply summed by directing attention to the scaling and tailoring of hardware to the needs peculiar to IUS application. The scale of observation and thinking applied to the utility scenario is much too large for the IUS.

The smaller scale of the IUS application favors a more rapid advancement toward detailed design for a pilot demonstration installation than for a much more ambitious utility-scale application.

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TABLE 7.3. SUMMARY OF COSTS FOR COMPRESSED AIR ENERGY STORAGE SUITABLE FOR IUS APPLICATION

Item	Unit Cost
Power Related Equipment	
Compressor	\$ 30/kW
Hot Gas Generator	\$ 44/kW
Electrical Generator	\$ 59/kW
Subsystem Interfacing Equipment	\$ 5/kW
Installation	\$ 20/kW
SUBTOTAL	\$158/kW
Energy Storage Related Equipment	
Air Storage Facility (Hard Rock Cavity)	\$ 50/kWh
Operation & Maintenance (O & M)	
Fuel (No. 2 distillate oil)	7.28 mills/kWh
Remainder of O & M	10 mills/kWh

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8. THERMAL ENERGY STORAGE

Thermal energy storage systems are defined, for the purposes of this study, as storage systems which are charged and discharged via the transport of thermal energy across the storage system boundaries. The actual energy content of a thermal storage system may manifest itself as a change in the temperature of a material, as a change in the physical state of a material, or as a change in the chemical composition of a system. This definition does not include the utilization of thermal energy in thermochemical processes for the production of fuels as this particular concept is considered to be a form of chemical energy storage.

Basic Components and Operation

Thermal energy storage (TES) systems may be viewed as consisting of a thermal storage material, a vessel for containing the TES material, and a means for transporting thermal energy to and from storage. A fourth area for consideration is the method of integrating the thermal store within the energy system under consideration.

Thermal Storage Material

Most thermal storage concepts can be classified as either sensible storage or phase change storage. Sensible storage involves the addition (or removal) of thermal energy to (or from) a material during charging which results in an increase (or decrease) in temperature of the storage medium. The average temperature of a sensible storage material is, therefore, a measure of the degree of charge (or the energy content) of the thermal storage unit. The thermal energy contained in a sensible storage unit is given by

$$E = MC (T - T_{\text{ref}})$$

where

- E = Energy content, J (Btu)
- M = Mass of the system, kg (lbm)
- C = Specific heat of the storage material, J/kg K (Btu/lbm F)
- T = Temperature of the system, K (F)
- T_{ref} = Temperature at which the energy content is considered to be zero, K (F)

Obviously, sensible storage materials should have a high specific heat, high density, and wide temperature range. In addition, the sensible storage material should be inexpensive, readily available in large quantities, nonhazardous, stable for long periods of time, and environmentally acceptable.

The leading candidate material for sensible storage is water. Water is essentially free, abundant, nontoxic, and possesses good heat transport properties. In addition, a vast body of engineering data and experience are available on its use. For these reasons, water storage has been chosen as a baseline storage system for this study. Unfortunately, water has a relatively high vapor pressure which necessitates the construction of expensive pressure vessels for containment if operation of the storage system at temperatures greater than 373 K (212 F) is desirable.

Other candidate materials for sensible heat storage include rocks, scrap iron, and oils. Although the heat capacity for these materials is less than water, they do not possess the high vapor pressure of water thereby offering potential savings in containment vessel costs if operation above the boiling point of water is necessary.

Phase change materials store energy as the latent heat of transformation between two physical phases (usually the alternate melting and solidification of a substance). The phase change process normally occurs at a constant temperature--an important advantage of this method of energy storage. The energy content in a phase change energy store can be expressed as

$$E = M [C_S (T_f - T_{ref}) + H_f + C_L (T - T_f)]$$

where

E , M , T , and T_{ref} are as before and

C_S = Specific heat of solid phase, J/Kg K (Btu/lbm F)

C_L = Specific heat of liquid phase, J/Kg K (Btu/lbm F)

H_f = Latent heat of fusion of the material, J/Kg (Btu/lbm)

T_f = Melting temperature of material, K (F)

Desirable properties for phase change materials include a high heat of fusion as well as high specific heat and density. In addition, the melting temperature must be in a range which is compatible with the intended application. Materials suggested for phase change storage in the temperature range suitable for IUS include paraffins, inorganic salt hydrates, and clathrate hydrates. Although the energy storage density for phase change storage is generally higher than for sensible storage, phase change materials generally possess a relatively low thermal conductivity. This complicates the problem of transferring heat to and from storage and generally results in rather complicated (and therefore expensive) heat exchanger designs.

Phase change materials, like sensible storage materials, should be inexpensive, readily available, nonhazardous, stable for many cycles of charge/discharge, and environmentally acceptable.

Storage Vessels

The primary purpose of the storage vessel in TES systems is to contain the storage material. The vessel can also act as a means for insulating the storage system to reduce heat losses and as a portion of the heat addition/removal system. For most thermal storage systems, the cost of the storage vessel represents a substantial portion of the total storage system cost. It is therefore important that storage vessel costs be minimized if thermal storage systems are to become economically practical.

Heat Exchanger Designs

Thermal energy must be transferred to and from the storage material in all thermal storage devices. The heat exchanger designs by which this heat transfer is accomplished may be lumped into one of two categories--direct contact heat exchangers and indirect heat exchangers.

As the name implies, direct contact heat exchangers allow the working fluid (the material utilized to transport the thermal energy from the heat source to storage and/or from storage to the thermal load) to come in intimate contact with the storage material. This can be accomplished when the working fluid and the storage material are the same fluid (such as water storage with a water distribution system) or where the working fluid and the storage material are such that they can be kept separated (as in a rock bed storage system with air as the working fluid). Direct contact heat exchangers are very efficient since the distances through which heat must be transported can be kept quite small.

Indirect contact heat exchangers utilize a metal wall to separate the working fluid from the thermal storage material. Indirect heat exchangers can be either the conventional shell and tube type exchanger, or a "fixed-bed" type exchanger where the storage material remains essentially at rest and the working fluid is circulated through passages to deposit or collect thermal energy.

Methods of Integration

Thermal energy storage devices are subsystems which must be integrated into larger energy systems in order to be useful. It is therefore impossible to properly assess thermal storage concepts without considering the integration of the TES system into the larger energy system. In this study we are concerned with utilizing energy storage devices in conjunction with Integrated Utility Systems (IUS) in order to reduce the energy consumption and/or the cost of supplying utility services to communities.

In order to assess the alternative energy storage systems on a common basis, a baseline IUS was selected. This baseline system, which is described in greater detail in Volume II of this report, basically consists of diesel engine driven electrical generators which are equipped with lube oil, water jacket, and exhaust gas heat recovery units. Thermal energy recovered from the engines is supplemented by a heat recovery solid waste incineration unit and, if necessary, an auxiliary oil fired boiler in order to supply space heating and hot water heating for the buildings being served. Space cooling is supplied via absorption units which are supplemented by electrically driven centrifugal units when necessary.

The baseline IUS contains three sources of thermal energy which may be used to charge a thermal storage system. The highest temperature source is the 394 K (250 F) steam loop which is fed by the water jacket and exhaust gas heat recovery units, the incinerator, and the auxiliary boiler (if present). Another potential source of thermal energy is the lube oil heat recovery loop, which operates at a temperature of 180 F. The final source of thermal energy is water produced by the chillers (assumed to be 280 K (45 F)). Energy withdrawn from thermal storage may be used to supply space heating and hot water heating requirements via the hot water distribution system (which maintains a send-out temperature of 367 K (200 F) and a return temperature of 333 K (140 F)) or for space cooling by means of the chilled water distribution system (which operates between the temperatures of 280 K (45 F) and 287 K (57 F)).

Identification and Description of Alternative Concepts

A review of the literature reveals a number of concepts for thermal energy storage which have possible application to IUS. These include:

- Hot and cold water storage
- Annual cycle ice storage
- Thermal wells
- Paraffins
- Oil storage
- Liquid metals

- Rock storage
- Reversible chemical reactions
- Heat of vaporization
- Adsorbent systems
- Inorganic salts
- Inorganic salt hydrates
- Clathrate and semiclathrate hydrates
- Molten semiconductors.

Each of these concepts will be discussed briefly in the following paragraphs.

Hot and Cold Water Storage

As mentioned earlier, thermal storage utilizing the sensible heat of water has been chosen as the "baseline storage system" for this study. It therefore serves as a yardstick for the comparison of other energy storage devices. The selection of water storage as the baseline storage system was made prior to the initiation of the study and was based on the fact that water appeared to be particularly well suited to IUS application. Water is used to distribute thermal energy throughout the complex or community thus simplifying the integration of the thermal storage subsystem with the IUS. Moreover, water is readily available, inexpensive, and a considerable amount of engineering experience exists on its use.

A water storage system has the advantage of being able to store heat during the winter months as well as to store chilled water during the summer. It is difficult to estimate the number of existing installations utilizing water as a thermal storage medium. A recent article⁽¹⁾, however, reports that there are over 70 existing solar energy systems which utilize water storage systems. Another source⁽²⁾ estimates that in Japan alone thermal storage with water is used in conjunction with about 5 million square meters of building floor space.

Annual Cycle Ice Storage

Recent studies carried out at Oak Ridge National Laboratories^(3,4,5) have revived interest in a concept which utilizes ice for the storage of energy on a seasonal basis. The concept is known as Annual Cycle Energy Storage (ACES)

and is normally envisioned as a means of reducing the energy requirements of residences or commercial buildings which are serviced by conventional utilities. ACES utilizes a heat pump to provide the space heating requirements of the building during the winter. The heat pump evaporator withdraws energy from a specially constructed water tank, causing the temperature of the tank to drop until the water begins freezing. During the freezing process, the latent heat of fusion of the water serves as the source of heat for the heat pump with the source temperature remaining at a nearly constant 273 K (32 F). The freezing process continues throughout the heating season so that a considerable amount of ice accumulates. This ice is stored until the summer months, when it is used to supply the cooling loads of the building. The system is actually a seasonal storage system (hence the name Annual Cycle Energy Storage).

A variation of the ACES concept which would be applicable to Integrated Utility Systems utilizes a heat pump to supply the auxiliary heating requirement which is normally satisfied by an auxiliary boiler in the "No Storage" IUS. The ice manufactured by this heat pump is then available to supply cooling loads during the summer months. This ice supply is used to satisfy that portion of the cooling load which is not met by absorption air conditioning.

Thermal Wells

The utilization of thermal wells as energy storage devices has been examined by Meyer and Todd.⁽⁶⁻¹⁰⁾ The concept involves the injection of pressurized hot water into an aquifer (Figure 8.1). The injected water will be less dense than the native groundwater due to its higher temperature, and will displace the colder water downward. The hot water/hot porous rock combination acts as a thermal storage medium which can be discharged by reversing the flow of water from the well. Since heat losses increase in proportion to the area, while the storage capacity increases in proportion to the volume, thermal storage wells offer potential for low heat losses due to the high volume to area ratio possible. Meyer and Todd calculate that approximately 75 percent of the stored heat could be recovered after 90 days of storage.

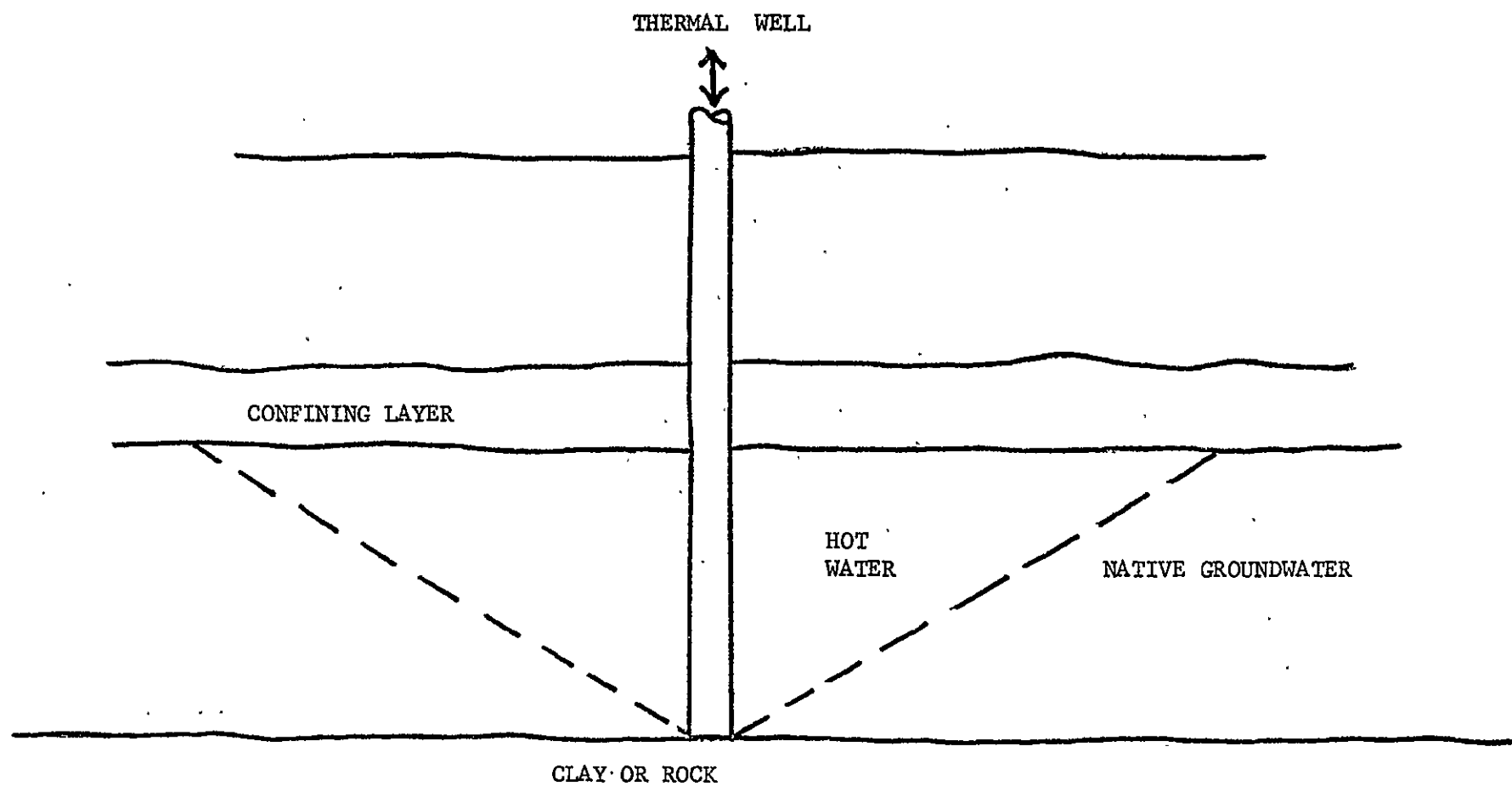


FIGURE 8.1. THERMAL WELL ENERGY STORAGE

Oil Storage

The use of heavy fuel oils or other organic liquids as thermal storage materials has been considered*. These liquids, which would store energy as sensible heat, have the advantage of possessing a relatively low vapor pressure at the higher temperatures envisioned for some thermal storage applications. Thus the storage vessel necessary for containing the liquid does not need to be designed for the high pressures which would be necessary if water were used as the storage material. Savings in the cost of this vessel can therefore be realized. The specific heat of residual (No. 6) fuel oil is about 2.09 kJ/Kg K (0.5 Btu/lbm F), or about one half of the specific heat of water.

The utilization of oil storage in conjunction with IUS does not appear to be feasible due to the fact that high temperature storage is not required in this system. The highest temperature energy recovered in the IUS baselines is 394 K (250 F) and the hot water distribution system send-out temperature is 367 K (200 F). The oil storage scheme therefore has no advantage over a water storage system which can operate up to a temperature of 367 K (200 F) without requiring a pressure vessel.

Liquid Metals

The possibility of utilizing liquid metals (sodium and potassium) as a sensible heat storage medium has been suggested. The concept would be similar to the storage of thermal energy in hot water, but, like the oil storage concept discussed above, it would take advantage of the fact that liquid metals have a lower vapor pressure than water. Hence operation at a higher temperature could be realized. The liquid metal storage concept was not pursued further for application to IUS due to the safety problems inherent in this concept as well as the absence of a requirement for high temperature storage in IUS.

Rock Storage

The storage of thermal energy in the sensible heat of rocks has been utilized in a number of installations⁽¹⁾. These systems normally utilize air as the working fluid, although the use of water as a working fluid is not inconceivable.

* A major oil company is known to be looking into this concept but details are not available at this time.

The thermal well concept is viewed as a means for storing energy on a seasonal basis. The storage would be utilized to accept otherwise unusable high grade heat during the fall and spring seasons when heating and cooling loads are low. This heat could then be recovered during the winter months to supply the auxiliary heating requirements of the IUS.

Paraffins

The storage of thermal energy as the latent heat of fusion of paraffins has been proposed by a number of researchers.⁽¹¹⁻¹⁵⁾ The material appears to be well suited to thermal storage applications since it possesses a relatively high heat of fusion, has melting points in a generally suitable temperature range, is inexpensive, and is readily available. The primary advantage of utilizing a phase change storage material is the increased energy storage density (and hence reduced volume of storage) compared to sensible heat storage systems. This advantage becomes more pronounced as the temperature swing* of the thermal storage system is reduced. Thus, paraffin storage devices appear to be particularly attractive for those applications where the temperature swing is limited.

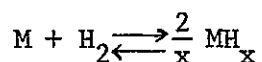
The application of paraffin storage devices is complicated by the fact that the thermal conductivity of the material is relatively low. This requires that the distances through which heat transport takes place be kept small in order to insure that the storage device may be charged and discharged at a reasonable rate. Thus, the cost of the heat exchanger for paraffin storage systems can become substantial. In addition, paraffins undergo a significant volume change (~10 percent shrinkage) upon solidification. The design of the heat exchanger must be such that this shrinkage does not inhibit the heat transfer process.

* The temperature swing of a thermal storage system can be considered to be the difference between the temperature of the system when fully charged and the temperature when completely discharged.

Since the specific heat of rocks is only about one-fifth that of water, a rock storage system does not appear to offer any advantages over a water storage system for IUS application and, therefore, is considered further in this study.

Reversible Chemical Reactions

Thermal energy may be stored as the heat of reaction of several reversible chemical reactions. A particular system which has been suggested⁽¹⁶⁾ utilizes the heat of reaction of hydrogen/metal-hydride systems. The concept (shown in Figure 8.2) involves utilizing available thermal energy to heat a metal hydride, thereby driving the reaction



to the left and releasing molecular hydrogen. The released hydrogen is stored under pressure in a separate container. When thermal energy is required, the hydrogen is allowed to recombine with the metal and the above reaction proceeds to the right, giving up the heat of reaction. Although this scheme appears to be attractive on an energy storage per unit weight basis, the energy storage per unit volume is substantially less than other thermal storage devices due to the large volume required for the storage of hydrogen gas. Gruen and Sheft⁽¹⁷⁾ propose to eliminate the need for hydrogen storage tanks by including a second metal-hydride system which would store the hydrogen released from the first metal hydride during charging.

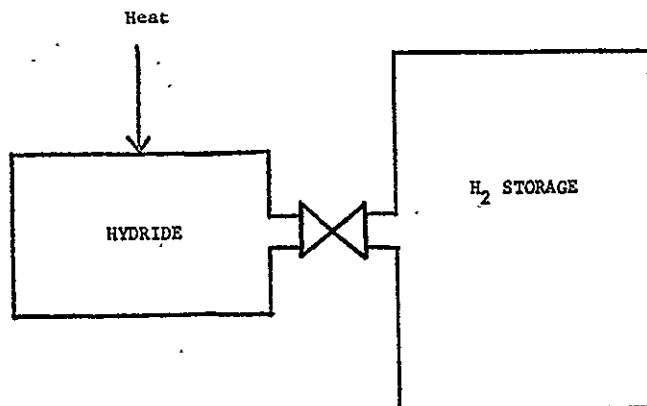


FIGURE 8.2. METAL HYDRIDE THERMAL STORAGE

Although these metal-hydride systems, as well as several other chemical reaction storage systems, (18,19) appear to have potential for developing into feasible energy storage alternatives, considerable research and development must be carried out before meaningful assessments can be made. It appears, however, that integration of these storage devices into IUS will be difficult due to the relatively high temperatures required for charging and the inherent complexity of these systems.

Heat of Vaporization

Heat may be stored in the vapor phase of a substance and released when the vapor is condensed to a liquid to reclaim the latent heat of vaporization. (20) Although the heat of vaporization on a mass basis is quite high for many substances, (e.g., 950 Btu/lb for water) an energy storage system utilizing vapor storage would be excessively large due to the need to store the very low density vapor. Heat of vaporization storage systems are, therefore, not considered further in this study.

Adsorbent Systems

Heat is evolved when certain gases are adsorbed in materials such as silica gel. A discussion of a system employing this concept in connection with providing solar crop drying is presented in Reference 21. The concept does not appear to be applicable to Integrated Utility Systems, however, and adsorbent systems were not considered further in this study.

Inorganic Salts

Thermal energy storage as the latent heat of fusion of inorganic salts has been proposed, (22-26) but little actual experience has been published on the performance of these systems. Some experimental information is available as a spin-off from space applications. (27-33) Materials mentioned as candidates include eutectic mixtures of metal fluorides (NaF , CaF_2 , LiF , MgF_2) as well as sodium nitrate and several chloride salts. The melting points of the inorganic salts, however, are generally greater than the temperatures of the available thermal energy in IUS.

Inorganic Salt Hydrates

Extensive investigations into the use of inorganic salt hydrates as phase change materials in thermal storage systems has been undertaken. (34-40) These materials are compounds of inorganic salts and water, the best known being Glauber's salt ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$). Other salt hydrates which have been considered include calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$), and sodium thiosulfate pentahydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$). These materials possess high latent heats of fusion and are relatively inexpensive.

The application of the salt hydrates to thermal storage systems has been hindered due to the fact that these materials generally melt incongruently. The result of this behavior is that the anhydrous salt formed sinks to the bottom of the container and, upon subsequent freezing, does not recombine with water. Thus, there is a reduction in the apparent heat of fusion as the mixture is repeatedly cycled. Many thickening agents and encapsulation techniques have been attempted with the objective of solving this problem but no completely successful solutions have been reported to date.

Clathrate and Semiclathrate Hydrates

The use of clathrate and semi-clathrate hydrates as a phase change thermal storage material is discussed in Reference 34. These materials are continuous solid water structures which contain cavities within which guest molecules reside. The guest molecules act to stabilize the ice structure. Although these materials offer promise as TES materials, the information which is available is not sufficient to allow an assessment of their applicability to IUS. Therefore, they were not treated further in this study.

Molten Semiconductors

The use of molten semiconductors as a thermal storage material is suggested in Reference 41. The material proposed is $\text{Ge}_{0.4}\text{S}_{0.6}$ which has a eutectic temperature of 863 K (1,094 F). It has a positive coefficient of expansion in

the liquid but contracts on melting. It is therefore claimed that the material would simplify heat exchanger design since the solid phase would exist above the liquid phase. The transfer of heat into and out of the store could then occur at the bottom of the tank and convective currents in the liquid would assist rather than impede heat transfer. The high melting temperature of these materials, however, rules out their application to IUS.

Selection of Concepts to be Treated in Greater Detail

A number of the thermal storage concepts discussed in the previous section are obviously not suited for application to integrated utility systems. Several of these can be ruled out due to a mismatch between the temperatures required for the storage device and the temperature ranges of interest for IUS. This consideration eliminates molten semiconductors, inorganic salts, liquid metal systems, and the majority of the reversible chemical reaction systems. Heat of vaporization systems are eliminated due to the large storage volume required while adsorbent systems are ruled out as not being compatible with IUS. Clathrate and semi-clathrates were eliminated from further consideration since available information on this concept is insufficient to carry out a meaningful assessment.

The remaining thermal storage concepts appear to be amenable to integration with IUS. It was, however, decided to eliminate three more of these from further consideration. Oil storage and rock storage were ruled out since neither of these systems offered a significant improvement in performance nor possible reduction in the cost of the storage system over the baseline water system. The inorganic salt hydrates were not considered further due to the absence of a near term successful solution to the incongruent melting problem.

The remaining four thermal storage concepts which were selected for analysis in greater detail include

- Hot and cold water storage
- Annual cycle ice storage
- Thermal wells
- Paraffins.

It was thought that the selection of these concepts would "bracket" the thermal storage field due to the fact that the water storage system represents a "present-day" solution to the thermal storage problem while the remaining three would offer potential improvements in performance or reduction in cost of future IUS.

Assessment of Selected Concepts

The assessments of technical and cost characteristics of thermal storage systems which are presented in the following sections were developed based on assumed IUS configurations. These "baseline" IUS designs, which are discussed in more detail in Volume II of this report, were selected to represent a range of community sizes which would be suitable for IUS application. The two configurations selected consisted of an IUS which would supply a 1,000-Unit Apartment and an IUS for a portion of a community termed a "Village Complex". Both of the baseline IUS installations were assumed to be located in the Washington D.C. area. The baseline configurations were treated as design points for the purposes of integrating thermal storage systems, sizing equipment, and developing cost information.

Water Storage

Description of Principal Components and Operation. The water storage concept utilizes the sensible heat of water to store thermal energy. The water is contained in a tank which operates at atmospheric pressure, thus limiting the maximum temperature of operation to about 367 K (200 F). During the heating season, the tank is used to store hot water and operates on a daily cycle. When the electrical demand on the IUS is high and the thermal demand is low, there will be an excess of high grade thermal energy. This energy (which would be rejected to the atmosphere if storage were not available) is added to the water tank resulting in an increase in the average temperature of the water in storage. This energy may then be withdrawn from storage at a later time to satisfy space heating and domestic hot water heating demands which would otherwise be supplied by operating an auxiliary boiler. Thus, the net effect of adding thermal storage during the heating season is a reduction in the energy consumption of the IUS.

A water storage system may also be used to store chilled water during summer months. This results in the elimination of that portion of the electrical generating capacity which would otherwise be necessary to power electric chillers during peak cooling hours. The peak cooling demands are met by drawing on the chilled water which is contained in storage. The storage tank is recharged during the early morning hours when excess generation capacity is available. The load factor on the generator sets is thereby improved and considerable capital savings can be realized due to the reduction in required generator capacity. In addition, some improvement in the COP of the chillers can be expected due to their increased operation at periods of the day when ambient temperatures are lower.

Integration with IUS. Figure 8.3 is a schematic diagram showing how the water storage tank might integrate with the baseline IUS configuration for winter operation. The space heating and hot water heating loads imposed on the IUS are supplied via a hot water distribution system with a send-out temperature of 367 K (200 F) and a return temperature of 333 K (140 F). In a no-storage IUS, the energy required to satisfy these loads is supplied at two temperature levels. Engine lube oil heat recovery is used to supply low grade energy (assumed to be at a temperature of 355 K (180 F)) while high grade heat recovered from the engine water jacket, exhaust gas heat recovery, and incinerator heat recovery is in the form of low pressure steam. High grade energy may also be supplied, if necessary, via an auxiliary boiler. In the storage configuration envisioned, the storage tank will be used to supply the thermal energy necessary to raise the temperature of a portion of the water flow from the return temperature to the final send-out temperature.

Figure 8.4 is a schematic showing a possible integration technique for water storage during the summer months. The chilled water distribution system has a send-out temperature of 281 K (45 F) and this water is returned at 287 K (57 F). It is envisioned that the storage system would be discharged by dividing the return flow and sending a portion to the storage tank inlet while drawing stored chilled water from the tank outlet. This chilled water will be added to the water from the chillers to supply the cooling load. The tank will be recharged in the reverse procedure.

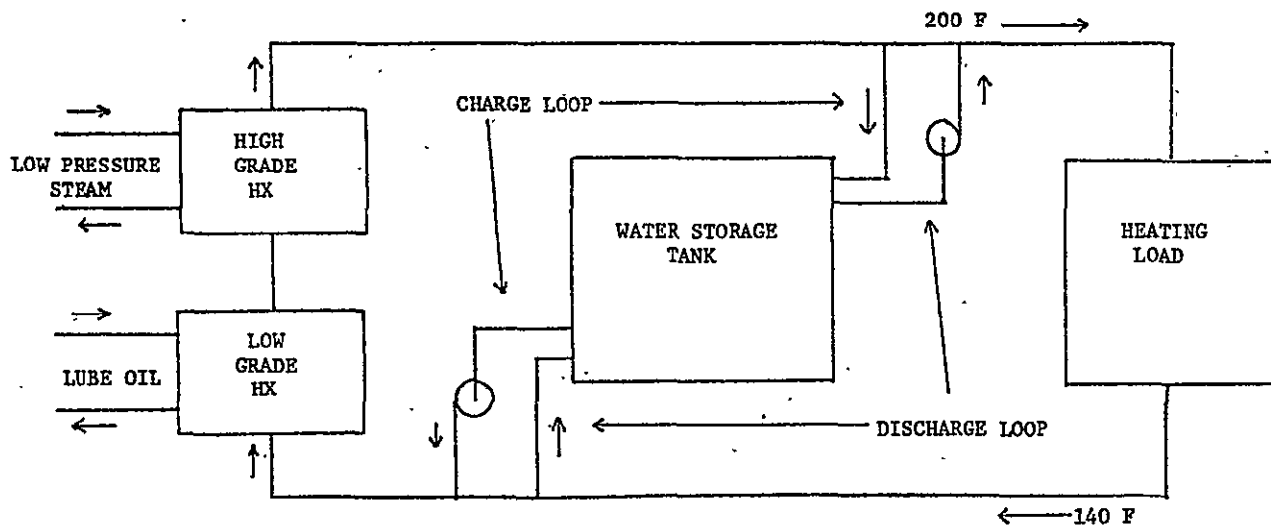


FIGURE 8.3. WATER STORAGE SYSTEM FOR WINTER OPERATION

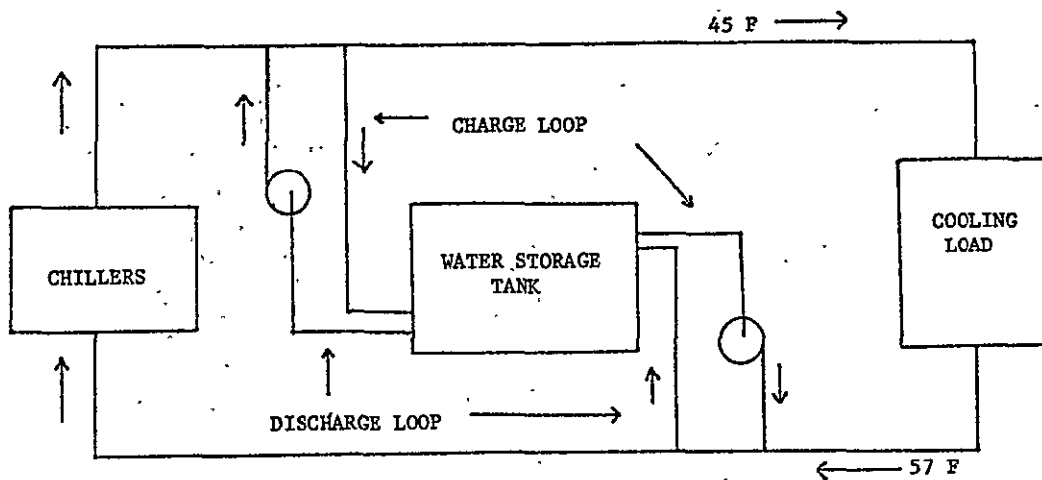


FIGURE 8.4. WATER STORAGE SYSTEM FOR SUMMER OPERATION

It should be pointed out that a number of other arrangements are possible for integrating the storage system. Several of these are discussed in more detail in Volume II.

Storage Tank. Due to the large storage volume which will be required for IUS water storage systems, it will be desirable to locate the storage tanks underground. It may be possible to integrate the tank into the design of one or more of the buildings making up the complex served by IUS, but a more likely arrangement would be to locate the tanks near, and possibly beneath, the building which houses the IUS equipment. For the purposes of developing cost characteristics for this system, it will be assumed that the storage tank is buried near the IUS building but not beneath it.

A good discussion of various tank materials and designs is contained in Reference 42. Candidates for tank materials include concrete, steel, fiberglass-reinforced plastic, and various earth-liner systems. The large size required, however, favors concrete tanks for underground applications. The tank would be lined with a spray-on vinyl protective sealant. In addition, it will be necessary to install an anti-blending device to reduce the undesirable effects of blending of return water. It is anticipated that a series of baffles which would force the flow stream to travel a circuitous path between inlet and outlet will be utilized. The exact nature of this baffling device has not been determined and more work will need to be carried out to define and optimize the arrangement.

The temperature blending problem can be visualized by referring to Figure 8.3, which shows the assumed arrangement for hot water storage. When fully charged, the water in storage will be at a temperature of 367 K (200 F). As this water is drawn off to satisfy a portion of the heating load, however, return water at 333 K (140 F) will be blended back into the tank. The effect of this blending is that the temperature of the water drawn from the tank will tend to decrease with time. For a fully mixed tank with a constant flow rate and a constant inlet temperature, the temperature will decrease exponentially with a time constant defined by the ratio of the mass of water stored divided by the mass flow rate of water into (and out of) the tank. Thus, after a period of one

time constant, 63 percent of the tank will have been discharged. It should be pointed out, however, that the water being drawn from the tank at this point would not be useful since its temperature would be too low to satisfy heating demands. An obvious, though costly, solution to this blending problem would be to use two separate tanks each operating at a constant temperature—one at the high supply temperature and the other at the return temperature. It has been reported⁽⁴³⁾ that the baffling technique is effective in minimizing the temperature blending problem and therefore the two tank arrangement will not be necessary..

Piping and Controls. The piping and control systems perform the function of delivering thermal energy to and from the storage tank in the proper amounts and at the proper time. It is anticipated that the controls for the thermal storage system will be tied into the overall IUS control system which will include computer control capability. The design of the piping and control system is not expected to present major difficulties as considerable experience in the design of similar systems exists.

Technical Characteristics. **Storage Size.** In order to estimate the size of the water storage tank required for the IUS baselines, the load profiles for winter and summer design days were analyzed using a computer program developed for this purpose. The results of these runs are presented in Table 8.1. It should be pointed out that these capacities represent the energy which would be drawn from storage on a design day for each of the applications. For the summer case, this capacity would be sufficient for an infinite number of consecutive design days since the storage is drawn on for only a few hours each day and may be recharged at other times. For the winter design days, however, storage is being drawn on continuously during the day and therefore the capacities shown in Table 8.1 would supply storage sufficient for only a single winter design day.

The water storage system is integrated into the IUS baselines so that the maximum temperature swings available are 33 K (60 F) for winter and 7 K (12 F) for summer. Assuming no temperature blending occurs (as would be the case if

TABLE 8.1. THERMAL ENERGY STORAGE CAPACITIES REQUIRED
FOR IUS BASELINES

Application	Energy Storage Capacity, GJ	
	Summer Design (Ton-Hours)	Winter Design (Millions of BTU)
1000-Unit Apartment ^(a)	55 (4350)	117 (111)
Village Complex ^(b)	224 (17,700)	359 (341)

(a) Based on the replacement of two of the six generators required for "no-storage".

(b) Based on the replacement of one of the eight generators required for "no-storage".

two separate tanks of equal volume were used), the volume of water necessary to store the required energy can be calculated. The volume calculated by this procedure must be increased, however, to account for the effects of temperature blending. Reference 43 indicates that, with proper design of the antiblending baffles, storage efficiencies* of 90 percent may be achieved. Table 8.2 gives the storage volume required for each IUS application using this storage efficiency. Since the storage volume required for summer operation exceeds the winter volume required, the storage tank will be sized for summer storage.

Table 8.3 gives the energy storage densities calculated for water storage. The energy storage density is a useful parameter for comparing alternative energy storage devices. Care must be taken when computing energy storage densities, however, to insure that the comparisons are meaningful. For the water storage system, three distinct energy storage densities may be computed representing thermal storage for both summer and winter and an electrical equivalent energy storage density. The first two are useful in comparing water storage to other thermal storage concepts while the latter is used for comparison against electrical storage concepts. The electrical equivalent energy storage density can be defined as the equivalent electrical energy contained in storage (resulting from the replacement of electrical generating capacity) divided by the storage volume.

Losses. The losses which are associated with water storage systems for IUS application can be attributed to the heat leakage to or from the storage tank and to the additional electrical power required by the pumps which circulate the water to and from storage. Due to the large storage volume required for these systems, the ratio of tank surface area to volume will be quite small. It has been estimated that the heat losses from the tank can therefore easily be limited to less than 2 percent of the stored energy per day and, with proper insulation, could be reduced significantly below that.

* Storage efficiency for thermal storage devices is defined herein as the percentage of stored energy which may be withdrawn before the temperature drops to an unacceptable level.

TABLE 8.2. TANK SIZES REQUIRED FOR WATER STORAGE SYSTEMS

Application	Storage Volume, m ³ (ft ³)	
	Summer Design	Winter Design
1000-Unit Apartment	2,190 (77,400)	970 (34,200)
Village Complex	8,920 (315,000)	2,970 (105,000)

TABLE 8.3. ENERGY STORAGE DENSITIES OF WATER STORAGE SYSTEMS

Application	Energy Storage Densities		
	Winter Thermal, MJ/m ³ (BTU/ft ³)	Summer Thermal, MJ/m ³ (BTU/ft ³)	Electrical Equivalent, kWh/m ³ (kWh/ft ³)
1000-Unit Apartment	120 (3,250)	25 (670)	1.73 (.049)
Village Complex	120 (3,250)	25 (670)	1.73 (.049)

Since the storage tank will operate at atmospheric pressure, pumping energy will be required to supply water from storage to the pressurized distribution system. Preliminary calculations indicate that this energy could be significant. Assuming the pressure differential is 620 kPa (90 psi), the pumping energy required will be about 10 percent of the electrical equivalent of the chilled water in storage on a summer design day. Winter pumping requirements will be less due to the reduced water flow rate. Careful design will be necessary to minimize this energy expenditure. Reference 44 reports the development of an energy recovery transfer pump for reducing this loss.

Costs. The largest cost for water storage systems is associated with the storage tank. Table 8.4 shows cost breakdowns for concrete tanks suitable for both the 1000-Unit Apartment and the Village Complex. These costs were developed based on an assumed depth of 6m (20 ft) for each tank. The unit prices for this estimate were taken from Reference 44. Table 8.5 gives cost information for the total water storage system.

General Comments. Water storage for IUS application, while not considered strictly "off-the-shelf", does appear to be a technically feasible approach which could be built utilizing present day technology. A number of areas do require development work, however, with the primary example being the determination of the optimum baffle arrangement. Other areas of concern include the proper design of the transfer pumping arrangement to minimize pumping costs.

Safety problems associated with water storage are expected to be minimal as are environmental concerns. The system should be highly reliable as well. It is expected that water storage systems would be constructed on site and, since a single tank design is desirable, the system is not well suited to incremental expansion to accommodate community growth.

Annual Cycle Ice Storage

Description of Principal Components and Operation. The Annual Cycle Energy Storage (ACES) concept discussed in References 3-5 can be modified to be compatible with the IUS baselines under consideration as shown in Figure 8.5.

TABLE 8.4. WATER STORAGE TANK COST ESTIMATE

Item	Cost, Thousands of Dollars	
	1000-Unit Apartment (20' x 62' x 62')	Village Complex (20' x 125' x 125')
Concrete (@ \$150/yd ³ in place)		
Base (8" thick)	14.2	57.9
Top (12" thick)	21.4	86.8
Walls (12" thick)	27.6	55.6
Excavation and Backfill (@ \$4/yd ³)	11.4	46.3
Insulation (@ \$0.75/ft ²)	9.5	30.9
Vinyl Spray Coating (@ \$0.35/ft ²)	4.4	14.4
Misc. portholes, ladders, etc.	6.0	12.0
Antiblending Baffles (@ \$1.50/ft ² surface area)	<u>18.9</u>	<u>61.9</u>
TOTAL	113.4	365.8
Cost/gal	19.7¢/gal	15.7¢/gal

TABLE 8.5. COST ESTIMATE FOR WATER STORAGE SYSTEM

Item	Cost, Thousands of Dollars	
	1000-Unit Apartment	Village Complex
Tank	113	366
Pumps	6	11
Piping	20	40
Controls	10	15
Water treatment, Misc.	<u>5</u>	<u>10</u>
Total Storage System Cost	154	442
Cost/gal	26.8¢/gal	19.0¢/gal

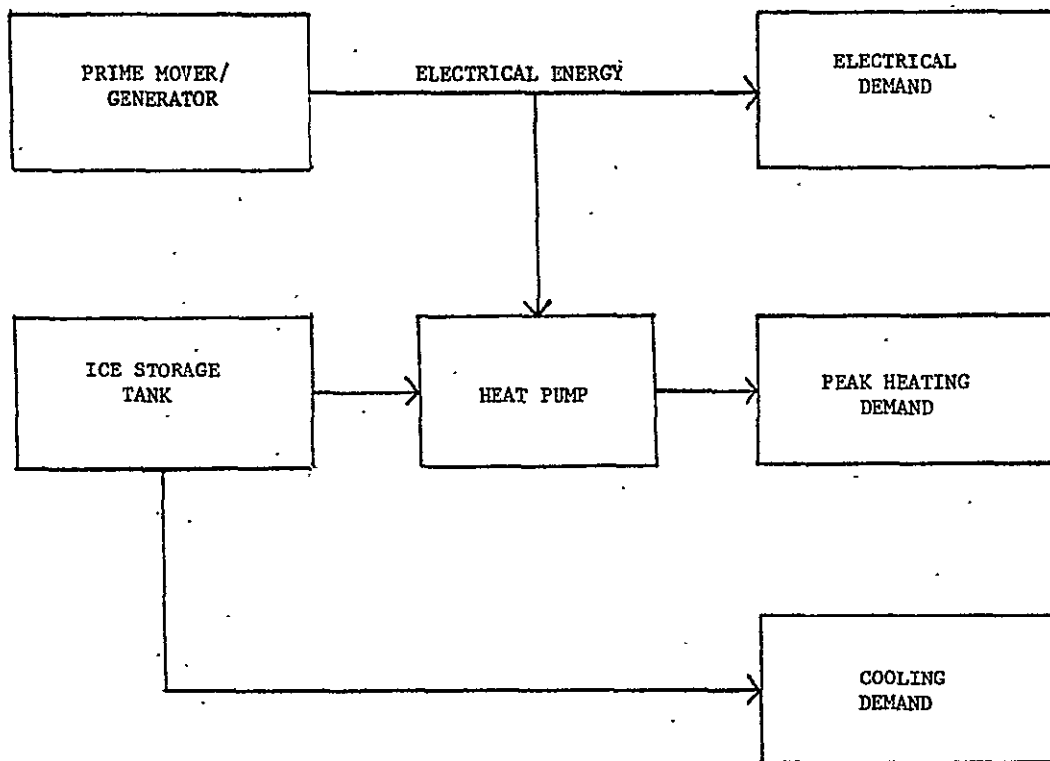


FIGURE 8.5. IUS WITH ANNUAL CYCLE ICE STORAGE

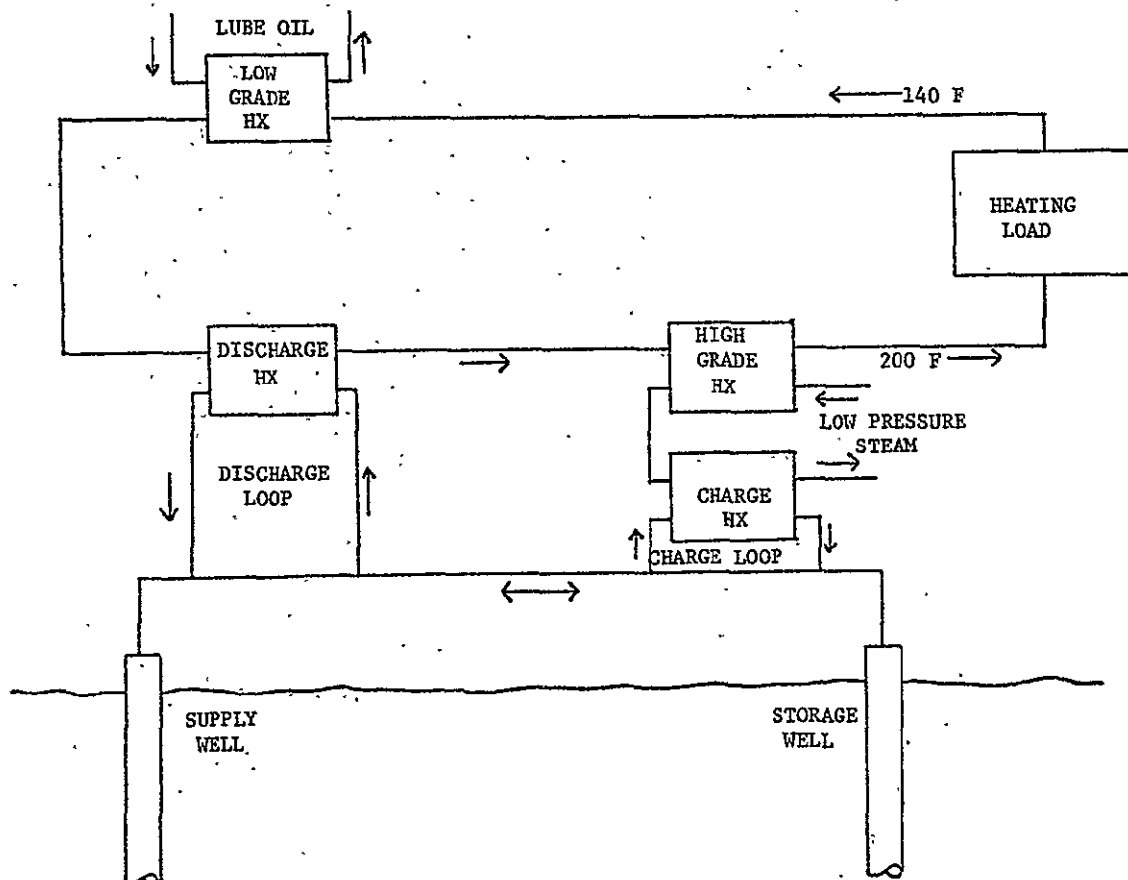


FIGURE 8.6. THERMAL WELL STORAGE FOR IUS

During periods when the demand for space heating and domestic hot water heating exceeds the amount of heat recovered from the prime movers and from incineration, a heat pump would supply the auxiliary heating required. This heat pump is powered by electrical energy generated by the prime mover, thereby increasing the amount of recoverable heat. The heat input to the heat pump evaporator would be drawn from a water/ice storage tank thereby freezing a portion of the water. The storage tank is sized so as to allow the freezing process to continue throughout the heating season. The ice which is manufactured during the heating season would be stored for use in satisfying cooling loads during the summer months and would be used only during those hours when absorption air conditioning is not sufficient to satisfy the cooling load.

Storage Tank. The storage tank envisioned for the ACES concept does not differ greatly from the tanks used for conventional water storage systems except that a series of extruded aluminum finned tubes are formed into serpentine throughout the tank. The ice formation takes place on these tubes which contain a circulating brine solution. The brine picks up the latent heat of fusion resulting from the ice formation and transports it back to the evaporator of the heat pump. The design of the coils must be such that damage due to the buoyant and expansive forces associated with the ice formation is eliminated.

Heat Pump. The ice storage concept will require a heat pump to provide the auxiliary heating during winter. Heat pumps which appear to be suitable for this are available on the market although their designs would have to be optimized to meet the lower evaporator temperatures associated with the ice formation.

Piping and Controls. As in the water storage concept, piping and controls will be required to effect the transfer of energy to and from storage. These will be considerably more complicated for the ice storage concept due to the need to transport thermal energy from storage via the brine solution and also to satisfy cooling loads via a water loop.

Technical Characteristics. Storage Size. Since the computer model developed during this study for analysis of IUS storage designs does not treat storage on a seasonal basis, it was necessary to estimate the size required for ice storage by hand calculations. The result of these calculations, which were based on the quantity of supplemental heat required on an average winter day, revealed that the 1000-Unit Apartment IUS would require a storage volume of approximately 4760 m^3 ($168,000 \text{ ft}^3$) while the volume of the Village Complex tank would be $24,700 \text{ m}^3$ ($873,000 \text{ ft}^3$). These volumes are over twice the storage capacity required for the water storage system discussed earlier.

It should be pointed out that, due to the relatively small amount of auxiliary heating required by the IUS in the location under consideration, the ice manufactured during the winter months will not be sufficient to supply cooling throughout the summer. Preliminary calculations indicate that the ice supply will be exhausted after 17 days of average summer cooling for the 1000-Unit Apartment IUS. After this time, however, the storage tank can continue to operate as a "conventional" water storage system for the storage of chilled water.

Fuel Savings. The fuel savings which result from the application of the ice storage concept to IUS are due to the reduction in auxiliary fuel required during the winter months and from reduced electrically driven refrigeration during the summer. The annual fuel savings from both of these sources total about 15,500 gallons of fuel per year for the 1000-Unit Apartment IUS (or about 2 percent of the total fuel consumption). For the Village Complex, savings would be about 68,000 gallons per year (about 1 percent of the annual usage).

Generator Capacity Required. The fact that the heat pump will require additional generator capacity during those periods when auxiliary heating is required brings up the question of the adequacy of the installed generator capacity. For the 1000-Unit Apartment case, the maximum auxiliary heating requirement is 3.69 MW ($12.6 \times 10^6 \text{ BTU/hr}$). Assuming a heat pump COP of 4.0, and taking the increased heat recovery from the prime mover into account, the increased power generation necessary to supply the heating requirement can be

calculated to be 782 kW. When added to the other electrical demands at this hour, it can be determined that 5 generator sets will be necessary to carry the load. Thus, for the 1000-Unit Apartment case, savings in the capital costs of only one generator set may be credited to the storage device (two generator sets could be replaced with the water storage system).

For the Village Complex, it appears that seven of the 4415 kW generator sets would be adequate to supply the increased electrical load during the winter months.

Heat Losses. Since ice storage is a seasonal storage concept, heat losses can be a potentially serious problem. Fortunately, the temperature difference between the ice bin (at 273 K (32 F)) and the surrounding earth will be small. A sample calculation on a tank sized for the 1000-Unit Apartment IUS shows heat losses on the order of 0.1 percent per day. This calculation assumed an R-19 insulation and a temperature differential of 22 K (40 F). Heat losses over a three month hold period could therefore be on the order of 10 percent of the storage capacity. Losses for the larger Village Complex tank will be less severe.

Costs. A crude cost estimate of the ice storage system described was attempted. These costs were based largely on discussions with researchers at Oak Ridge and from information taken from References 3-5. The results of the cost estimate are shown in Table 8.6.

General Comments on Annual Cycle Ice Storage. Annual cycle ice storage can be considered to be a concept which is currently in the developmental stages but has not, as yet, found commercial application. The concept appears to be technically feasible with the area of largest concern being the heat exchanger coil design. Researchers at Oak Ridge are currently building a prototype unit sized for a single residence.

It should be pointed out that the design discussed here was essentially scaled up from a residential size. Subsequent discussions with Oak Ridge researchers have suggested the possibility of eliminating the ice coil altogether by

TABLE 8.6. COST ESTIMATE FOR ANNUAL CYCLE ICE STORAGE SYSTEM

Item	Cost, Thousands of Dollars	
	1000-Unit Apartment	Village Complex
Storage tank (a)	180	760
Ice coil (@ \$1/ft ³)	170	870
Heat pump (@ \$100/ton)	80	190
Piping and Controls	<u>30</u>	<u>60</u>
TOTAL	460	1,880

(a) Based on same unit prices used in Table 8.4.

TABLE 8.7. COST ESTIMATES FOR THERMAL WELLS

Application	Cost, Thousands of Dollars
1000-Unit Apartment	100
Village Complex	170

employing heat pumps which would manufacture ice (much like ice making machines). The ice would then be transported to the ice bin for storage. This could yield a significant reduction in the cost of the ice storage system.

Safety and environmental concerns do not appear to be significant problem areas with the exception of the large size required for these systems. The reliability of the concept has yet to be determined but it is expected that reliability could be equal to or greater than the reliability of the prime movers utilized in IUS. As with water storage systems, the bulk of the construction will take place on site and the expansion capability of the system will be limited.

Thermal Wells

Description of Principal Components and Operation. Figure 8.6 is a schematic diagram which shows how the thermal well storage concept might integrate with the IUS baselines under consideration. The concept would require two separate wells, one of which is utilized as the actual storage well and the other serving to supply the water required for injection into storage and serving as a depository for water drawn from storage during the discharge cycle. It will be desirable to maintain separation between the water drawn from these wells and the IUS distribution system water through the use of heat exchangers. The thermal wells concept, like annual cycle ice storage, is a seasonal storage system. During those periods when there is excess high grade thermal energy available (e.g. during the fall) water would be drawn from the supply well and heated to a high temperature (e.g., 383 K (230 F)) for injection into the storage well. This process would continue as long as excess energy was available. The hot water injected would tend to rise to the top of the confined aquifer displacing the colder water downward. Initially the injected water would give up much of its heat due to mixing with the cold water and porous rocks which make up the aquifer. As more hot water is injected, however, the temperature of the confined region will increase.

The thermal energy in storage would be recovered by drawing hot water from the storage well. This thermal energy would be used to satisfy the auxiliary heating requirements normally supplied by firing auxiliary boilers. Since the

amount of heat which is recoverable from the thermal wells increases as the minimum acceptable water temperature decreases, it will be desirable to supply the thermal load at the lowest possible temperature. It is also desirable, however, to utilize all of the low grade recovered energy possible. The energy drawn from storage will therefore be transferred to the distribution loop at a point between the lube oil heat exchanger and the high grade heat exchanger. The high grade heat exchanger is then utilized to bring the distribution water to the final send-out temperature of 366 K (200 F).

It should be pointed out that the arrangement described here will allow only a portion of the waste energy delivered to storage to be recovered for later use, even if heat losses from the thermal well could be eliminated completely. This is due to the fact that excess high temperature energy will be used to heat cold water drawn from the supply well to a high temperature prior to injection into the storage well. On discharge, however, the amount of energy extracted from the water which has been drawn from the storage well will be determined by the minimum temperature which will allow energy transfer to the distribution water. For the IUS baselines considered, this minimum temperature will be about 336 K (145 F). Thus, it will be necessary to inject warm water back into the supply well and the energy involved will not be recoverable.

Aquifers. Aquifers are geological formations consisting of a porous rock or gravel permeated by underground water. The water may be either fresh or salty. Of particular interest to the thermal well storage concept are the confined aquifers which have a layer of clay or other impermeable material forming the upper boundry of the aquifer. When hot water is injected into a confined aquifer, it will tend to rise until stopped by the confining layer.

An obvious limitation of the thermal wells concept will be the availability of suitable aquifer formations. It has been estimated that suitable aquifers are available at about 50 percent of the locations which would be of interest to IUS.

Wells. The major cost item for the thermal wells storage system is the wells. These would not differ greatly from conventional water wells except that they would require the capability to inject water into the ground as well as remove it.

Pumps and Associated Equipment. The equipment necessary for injecting and removing hot water to and from the thermal wells will be exposed to many of the same conditions that are encountered in the utilization of geothermal energy. The hot water will undoubtedly contain many dissolved minerals and will probably be highly corrosive. Thus the life of the pumps and piping for the thermal storage concept is in question. Considerable experience on the design of similar equipment is being amassed in connection with geothermal research as well as in connection with oil well recovery techniques. It is therefore expected that suitable pumps, heat exchangers, and associated equipment will be available.

Technical Characteristics. The concept of thermal storage utilizing aquifers has received attention primarily in connection with large central station power plants and very little information exists which would apply directly to the IUS application. For example, Meyer and Todd^(6,7) report the results of computer modeling of a thermal well which accepts and discharges water at a rate of $3800 \text{ m}^3/\text{day}$ (1×10^6 gallons/day). The 1000-Unit Apartment complex, on the other hand, would have an average injection rate of about $79 \text{ m}^3/\text{day}$ (2.1×10^4 gallons/day). The Village Complex would have an injection rate of about $1589 \text{ m}^3/\text{day}$ (4.2×10^5 gallons/day). The heat losses reported for the smaller IUS systems are, therefore, expected to be much higher than the 14 percent per season reported for the larger systems. Fortunately, the waste heat which is discarded during the spring and fall seasons for both IUS baselines is much greater than that required for auxiliary heating during the winter. Therefore, the high losses which would be associated with the relatively small thermal wells are not critical as long as the thermal energy which is maintained in storage is sufficient to satisfy the winter auxiliary heating requirement. As a point of reference, the thermal energy which would be available for storage

on an average fall day for the Village Complex is approximately 7 times the energy which would be required for auxiliary heating during an average winter day. For the 1000-Unit Apartment IUS, the wasted heat on a fall average day is only 1.5 times the winter average day requirement. It therefore appears that, while thermal wells may be a viable option for storage in connection with the Village Complex, the 1000-Unit Apartment IUS will not be amenable to this type of storage.

Costs. Although the preceeding discussions point out the limitations of the thermal well concept for application to the IUS baselines, it was felt that rough cost estimates would be desirable in order to further evaluate relative merits. Discussions with proponents of this concept have indicated that the cost figures reported in Table 8.7 might be appropriate for the 1000-Unit Apartment and the Village Complex IUS. These costs are based on an assumed 152 m (500 ft) well depth and include allowances for pumps, piping, controls, and heat exchangers.

General Comments on Thermal Well Storage. The possibility of using underground aquifers as a thermal storage medium is a concept which has yet to be demonstrated in an actual installation and therefore must be considered as a developmental energy storage technique. It is known, however, that Auburn University is currently under contract with the Office of Water Research to establish and experimentally evaluate a thermal well and this study should produce much valuable information.

The environmental effects of the thermal wells concept will need to be examined closely as the possibility of undesirable cross flows between the thermal wells and drinking water supplies will be present. In addition, the problem of fairly continuous withdrawal of water from one well and injection into another must be considered. Although the possibility of finding favorable solutions to these potential problems appears to be good, it would not be unreasonable to expect that the application of significant numbers of thermal storage wells might be limited due to environmental objections.

The thermal well concept does not appear to have any insurmountable safety hazards and the necessary equipment, while not considered off-the-shelf items, could probably be produced utilizing present day technology. As with the other thermal storage concepts under consideration, the bulk of this system would be fabricated in the field. Expansion capabilities will be determined by the characteristics of the aquifer utilized and is expected to be good in many cases.

Paraffins

Description of Principal Components and Operation. The baseline water storage system requires a large tank volume in order to meet the thermal requirements of the IUS. The volume of the storage tank, and hence its cost, is determined by the volume of water necessary to satisfy summer design day cooling loads. Since the water storage system is a sensible heat storage concept, the volume of water necessary is inversely proportional to the temperature swing through which the storage system operates. Efforts to reduce the volume required would, therefore, logically start with attempts to maximize this temperature swing.

The IUS baselines considered in this study have a chilled water send-out temperature of 280 K (45 F) and a return temperature of 287 K (57 F). It appears that some increase in this temperature swing can be obtained by lowering the chilled water supply temperature, although 278 K (40 F) should be considered as a minimum to avoid possible chiller freeze up problems. The lower temperature, however, will decrease the chiller efficiency and hence increase operating costs. The determination of the optimum operating temperatures for the chilled water system therefore requires a detailed tradeoff study. This analysis was not attempted and the 7 K (12 F) temperature swing was assumed throughout the study.

An alternate means for achieving reductions in the size of storage required for IUS would be to utilize a phase change material with a melting point within the temperature range of interest. Paraffins have been suggested as appropriate phase change material and a particular paraffin (C₁₅-C₁₆ by Enjay) has been identified⁽¹²⁾ as a suitable thermal storage material.

Integration. The storage concept envisioned can be considered to be a hybrid system combining a paraffin storage material with a water storage system. The paraffin would be sealed in suitable containers and these containers would be placed inside a water storage tank. A sketch of the proposed concept is shown in Figure 8.7. During winter operation, the temperature of the storage tank will be maintained above the melting temperature of the paraffin and the system will operate exactly the same as a "conventional" water storage system. During the summer months the tank will be used to store chilled water and at the fully charged condition, its temperature will be 280 K (45 F). As the storage system is called upon to supply cooling, the temperature of the water in the tank will rise and the phase change material will begin to melt thereby absorbing its latent heat of fusion from the water. The net effect is an apparent increase in the specific heat of the water contained in storage. The paraffin storage system therefore offers the possibility of substantial reduction in storage system volume.

The piping, controls, and operating procedure for the paraffin storage system will essentially be the same as to the water storage system discussed earlier.

Paraffin. A paraffin which appears to be well suited to IUS application is C_{15} - C_{16} . Reference 12 reports experimental determination of the properties of this material and the results are presented in Table 8.8.

Paraffin Containers. The design of the paraffin containers will be critical to the economic feasibility of the paraffin storage concept. Since the thermal conductivity of most paraffins is relatively low, the rate at which thermal energy can be conducted into and out of the material becomes an important design parameter. In order to assure an acceptable rate of charge and discharge, it will be necessary to minimize conduction distances and to maintain large heat transfer areas. This means that relatively small containers will be necessary. Several researchers⁽¹³⁾ have investigated the use of micro-encapsulation techniques and have reported some success. Another approach⁽¹¹⁾ has been to contain the paraffin in a series of shallow trays. The tray design has been assumed for the purposes of estimating costs of the paraffin system.

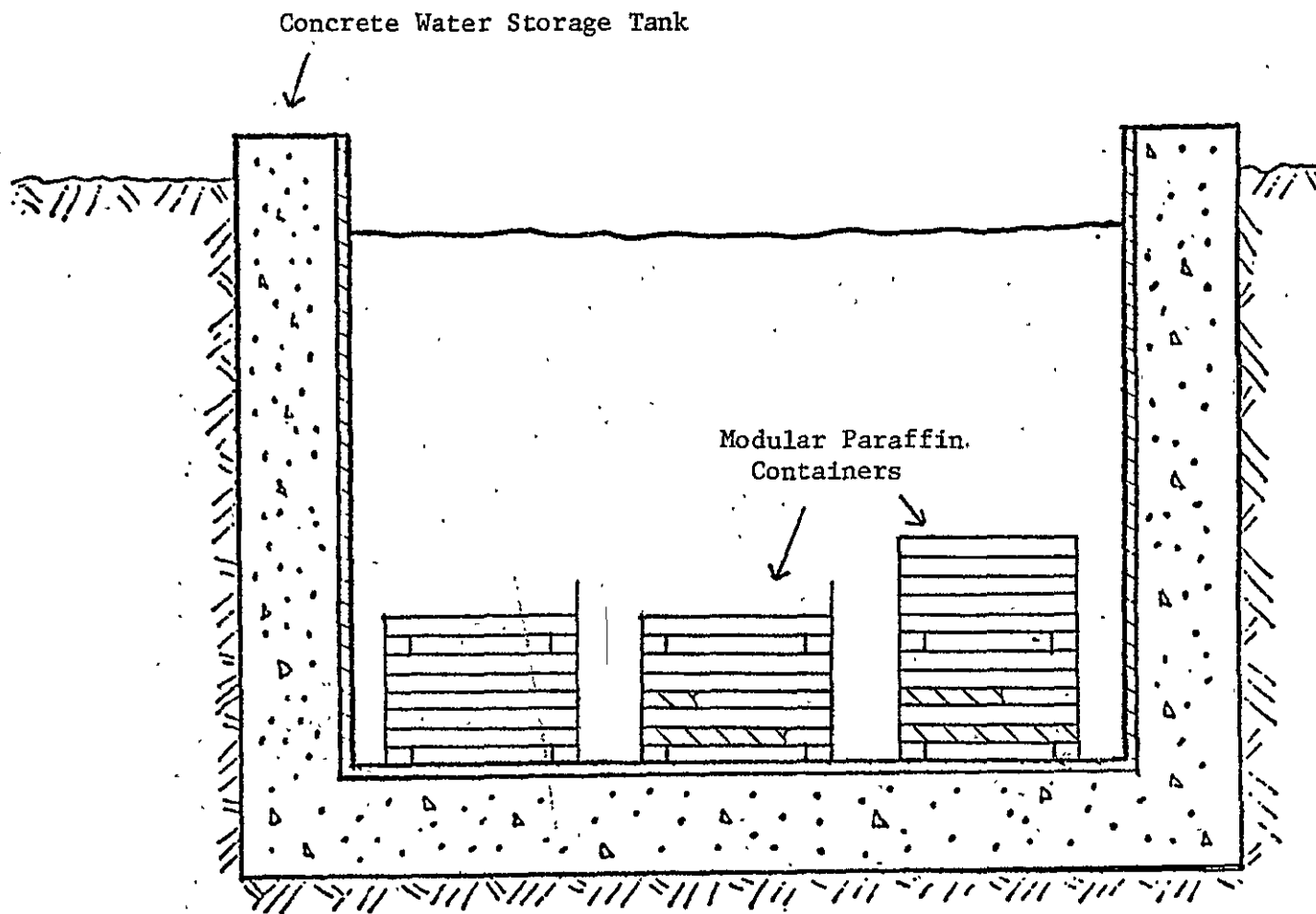


FIGURE 8.7. PARAFFIN STORAGE CONCEPT

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TABLE 8.8. PROPERTIES OF C₁₅-C₁₆ PARAFFIN^(a)

Property	Value	
Melting Temperature K, (F)	287	(47)
Latent Heat, KJ/Kg (Btu/lb)	31	(64)
Specific Heat, KJ/Kg ^o K (Btu/lb ^o F)	2.17	(0.52)
Density, Kg/m ³ (lb/ft ³)	780	(49)
Estimated Cost, \$/Kg (\$/lb)	0.11	(0.05)

(a) From Reference 12.

TABLE 8.9. SIZE CHARACTERISTICS OF PARAFFIN STORAGE

	1000-Unit Apartment	Village Complex
Storage Volume, m ³ (ft ³)	1,030 (36,400)	3,370 (119,000)
Paraffin Required, Kg (lb)	2.2 x 10 ⁵ (4.8 x 10 ⁵)	.95 x 10 ⁵ (2.1 x 10 ⁵)
Paraffin Volume, m ³ (ft ³)	276 (9,760)	1,230 (43,300)
Percent Paraffin, by volume	27	36

The volume change of paraffins upon solidification will be an important consideration in the container design. This shrinkage effect, which has been estimated to be about 10 percent, could give rise to voids in the solid paraffin and act to impede heat transfer. Proper container configuration will minimize this problem, however.

Technical Characteristics. A conceptual design of a paraffin storage system was completed based on a storage capacity sufficient to supply one winter and one summer design day. It should be noted that this storage system, when integrated with IUS, may not allow the replacement of the auxiliary boiler (as was assumed for the water storage case) as auxiliary energy may be required during long spells of severe winter weather. Sizing information resulting from this conceptual design are presented in Table 8.9.

Energy Storage Density. The energy storage densities for the paraffin storage system are shown in Table 8.10 for winter storage, summer storage, and the electrical equivalent for summer storage.

Costs. Since the performance of the paraffin storage system will be essentially the same as the baseline water storage system, it is apparent that the paraffin system will be economically justifiable only if the dollar savings resulting from a reduction in the storage volume is greater than the added cost of the paraffin and the containers. A rough cost estimate for the paraffin system is presented in Table 8.11. The tank costs for this estimate were based on the same unit costs as the water storage tanks presented in Table 8.4. The paraffin container costs are based on data presented in Reference 11.

When the cost estimates developed for the paraffin system are compared to the water system costs shown in Table 8.5, it is apparent that the dollar savings due to reduced tank size are overshadowed by the high cost of the container and that the total paraffin system cost is therefore greater than a comparable water system. It is interesting to note that the container cost would need to be reduced by approximately a factor of 6 in order for the paraffin concept to be cost competitive.

TABLE 8.10. ENERGY STORAGE DENSITIES OF PARAFFIN STORAGE SYSTEM

Application	Energy Storage Density		
	Summer Storage,	Winter Storage,	Electrical
	MJ/m ³ , Btu/ft ³	MJ/m ³ , Btu/ft ³	Equivalent, kWh/m ³ , kWh/ft ³
1000-Unit Apartment	54 (1450)	113 (3049)	3.74 (.106)
Village Complex	64 (1714)	107 (2865)	4.45 (.126)

TABLE 8.11. COST ESTIMATE FOR PARAFFIN STORAGE SYSTEM

Item	Cost, Thousands of Dollars	
	1000-Unit Apartment	Village Complex
Tank	64	159
Paraffin	24	105
Containers	149	651
Pumps	6	11
Piping and Valves	20	40
Controls	10	15
Water Treatment, Misc.	5	10
TOTAL	297	1,075

General Comments on Paraffin Storage. The paraffin storage concept described offers a means of substantially reducing the size of a thermal storage system for IUS application. It does not appear, however, that the dollar savings due to this reduction in size will be sufficient to offset the increased cost of the paraffin containers required. The container costs presented, however, are based on an assumed tray configuration. Other designs may subsequently be identified which could substantially reduce the cost. The micro-encapsulation technique mentioned above offers some promise in this direction.

Paraffins are flammable and caution will need to be applied when handling the material. This is, however, not expected to be a serious problem. The environmental impact of these systems will be approximately equivalent to water storage systems and should not be severe. The system is expected to be fairly reliable although replacement of tray sections which have developed leaks may be required periodically. Although the storage tank would be constructed on site, the paraffin containers will probably be fabricated elsewhere and transported to the site for installation. This will present no difficulties as the size of the trays will allow easy shipment.

The expansion capability of paraffin storage will be considerably better than any of the other thermal storage concepts discussed due to the fact that additional paraffin filled trays may be added as more storage is required. In fact, the paraffin trays could be used to add storage capacity to a water storage system which is no longer able to meet requirements due to increased cooling loads.

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